Hydrogeologic Characterization Report for the Rocky Flats Environmental Technology Site

Volume II of the Sitewide Geoscience Characterization Study

Text

Final Report
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EG&G ROCKY FLATS

Rocky Flats Environmental Technology Site
Golden, Colorado

Executive Summary

The Hydrogeologic Characterization Report was produced by the Environmental Restoration Program Division (ERPD) at the Rocky Flats Environmental Technology Site (RFETS or Rocky Flats site) as Volume II of the Sitewide Geoscience Characterization Study. The discussion of site hydrogeology complements and supports the Geologic Characterization Report (Volume I) and Groundwater Geochemistry Report (Volume III) and provides a sitewide description of groundwater flow systems at Rocky Flats.

Hydrogeologic data relevant to Rocky Flats were compiled from a variety of sources and are presented in this report. These data were analyzed and interpreted to provide a complete characterization of groundwater occurrence, distribution, and flow at the Rocky Flats site. The main objectives of the hydrogeologic characterization report were to :

1. compile, integrate, and standardize hydrogeologic data and reports in a consistent format;

2. provide a comprehensive conceptual model of surficial and bedrock groundwater flow; and

3. integrate and modify existing analyses of hydrologic data to develop up-to-date graphic representations of the hydrogeologic features of the site.

Included in the Hydrogeologic Characterization Report are maps displaying the temporal and spatial variation of the surficial groundwater at the Rocky Flats site, including maps showing the potentiometric surface, saturated thickness, saturated thickness difference, and average depth to groundwater. Maps of impermeable areas, groundwater diversion structures, springs and seeps, and hydrogeologic cross sections are also included. In addition, the results of recent hydrogeologic investigations are compiled in this report, including (1) the construction of more than 500 single-well hydrographs, involving the evaluation and subsequent correction of spurious water-level data, (2) the compilation of validated results from historical aquifer tests, and (3) hydraulic data for 99 slug tests.

Summaries of historical records, reports, and documents related to the hydrogeology of the Rocky Flats site and the surrounding area are presented in Appendix A (Review of Previous Hydrogeological Studies). These summaries include the purpose, information type, hydrogeological data presented, and conclusions of documents related to Rocky Flats site hydrogeology. Many of these documents, such as Annual RCRA Groundwater Monitoring Reports, OU-specific RI/FS reports, and the 1993 Well

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Evaluation Report provided the framework for the interpretations of the hydrogeology at the Rocky Flats site that are presented in this report. In addition, some reports or records identified as being potentially relevant to the Rocky Flats site hydrogeology were not located but were included in the bibliography.

The Rocky Flats site is located along the northwest margin of a regional aquifer system known as the Denver groundwater basin. The Denver groundwater basin is a large asymmetrical structural feature encompassing a 6,700-square-mile area and consists of regional aquifers of Cretaceous bedrock strata and unconsolidated Quaternary alluvial deposits. The alluvial aquifer includes present-day alluvial flood-plain deposits, unconsolidated surficial deposits along several ancestral drainages, and a series of alluvial terraces. Generally, the geologically younger terraces such as the Piney Creek Alluvium and the Broadway Alluvium are laterally connected and are in hydraulic connection to modern-day alluvial deposits. The geologically older terraces such as the Louviers Alluvium, Slocum Alluvium, Verdos Alluvium, and Rocky Flats Alluvium are present on topographically high ridges and are hydraulically interconnected with the modern-day alluvial deposits. Groundwater within the terraces is discharged as interflow through colluvial and landslide deposits or by discharge to seeps and tributary streams. Rocky Flats is located on an isolated remnant of the Rocky Flats Alluvium.

The four major bedrock aquifers of the Denver groundwater basin from youngest to oldest are the Dawson aquifer, Denver aquifer, Arapahoe aquifer, and Laramie/Fox Hills aquifer. Near the margins of the basin, groundwater within the bedrock aquifers is typically unconfined and generally flows in the direction of the surface topography. Recharge occurs in nearby outcrop areas or from the overlying alluvial aquifer. At greater depths within the center of the basin, the bedrock aquifers are confined by overlying shale strata. Under confined conditions, groundwater within the bedrock aquifers generally flows from highland recharge areas to lower elevation discharge areas beneath the South Platte River drainage located in the north-northeast part of the basin or toward the Monument Creek watershed, located in the southern part of the basin. Only the Arapahoe and Laramie/Fox Hills aquifers are present at the Rocky Flats site. The Arapahoe aquifer is very thin and is hydraulically connected with the overlying alluvial aquifer. The Laramie/Fox Hills aquifer is hydraulically separated from the overlying shallow groundwater system by hundreds of feet of confining shale.

The UHSU at the Rocky Flats site comprises Quaternary alluvium, colluvium, valley-fill alluvium, artificial fill, weathered bedrock of the undifferentiated Arapahoe and Laramie formation and all sandstones that are hydraulically connected with overlying surficial groundwater. The LHSU comprises unweathered claystone with interbedded siltstones and sandstones of the undifferentiated Arapahoe and Laramie formations. The contact separating the UHSU and LHSU is identified as the base of the weathered zone. The separation of hydrostratigraphic units is supported by the contrasting

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permeabilities of the units comprising the UHSU and LHSU, well hydrograph data indicating that the units respond differently to seasonal recharge events, and geochemical data reflecting distinct major ion chemistries in the groundwaters of the UHSU and LHSU. Well-cluster hydrographs exhibited similar fluctuations in hydraulic head within surficial deposits and weathered bedrock suggesting a hydraulic connection between the two sub-units of the UHSU. The major-ion chemistry of the surficial deposits and weathered bedrock groundwaters are generally very similar—typically classified as a calcium-bicarbonate type—supporting the concept that the two sub-units are in hydraulic connection. The major-ion chemistry of unweathered bedrock was more sodium-rich than groundwater in surficial and weathered bedrock deposits and was classified as sodium-bicarbonate to sodium-sulfate in composition.

Well-cluster hydrographs indicate that the UHSU and LHSU are hydraulically separated throughout most of the site. The relatively low vertical hydraulic conductivity of the LHSU (10^{-8} cm/sec) suggests that the LHSU effectively acts as a hydraulic barrier to downward flow. This is confirmed by differences in major-ion chemistry between the UHSU and LHSU. The slight shift in increased $\delta^{18}O$ and δD isotope content with depth and low tritium content in unweathered bedrock confirm that the hydraulic connection between the UHSU and LHSU is minimal. However, VOCs detected in some LHSU wells demonstrate a limited amount of recharge from the UHSU. Inferred northeast-trending bedrock faults may increase permeability in some areas, thereby enhancing the hydraulic connection between the UHSU and LHSU.

Groundwater in surficial deposits generally flows toward the east following the surface topography and relief of the bedrock pediment. Groundwater in the western part of the site generally flows east through the Rocky Flats Alluvium, which caps the terraced ridges. In the central part of the site, the terraced ridges are incised by modern-day drainages, where groundwater within the Rocky Flats Alluvium discharges to the surface at contact seeps along the slopes of the drainages or as interflow to the colluvium. Groundwater flow within the colluvium is directed toward the valley-fill alluvium covering the bottoms of the incised drainages. Groundwater within the valley-fill alluvium generally flows toward the east following the axis of the stream valleys. In the Industrial Area, incised paleochannels on the bedrock pediment act as preferential flowpaths within the surficial deposits in OUs 1, 2, and 4. In the eastern part of the Rocky Flats site, where the Rocky Flats Alluvium has been eroded, groundwater flow predominantly occurs in colluvial and valley-fill deposits. The hydraulic gradient is relatively flat and uniform in this area, implying that groundwater flow is not preferentially directed toward the stream valleys. The hydraulic conductivities (geometric mean) of the Rocky Flats Alluvium, colluvium, and valley-fill alluvium are 2.06E-04 cm/sec, 1.15E-04 cm/sec, and 2.16E-03 cm/sec, respectively.

Weathered-bedrock groundwater exists under both confined and unconfined conditions. Sitewide maps of groundwater flow within weathered bedrock were not constructed for this report due to limited data. However, maps from other reports, (i.e., Annual RCRA and OU-specific RI\FS reports) have shown that the configuration of the weathered bedrock potentiometric surface is similar to that of groundwater within surficial deposits. Therefore, it is expected that groundwater flow patterns in weathered bedrock resemble those observed in surficial deposits. Recharge to the weathered bedrock occurs primarily as downward seepage from the overlying surficial deposits and from direct recharge in outcrop areas west of the site. The main discharge components occur as downward seepage into the unweathered bedrock and into the colluvial deposits on the slopes of the incised drainages. The hydraulic conductivities (geometric mean) for the weathered-bedrock claystone, siltstone, Arapahoe Formation sandstone, and undifferentiated Laramie and Arapahoe formation sandstones are 8.82E-07 cm/sec, 2.88E-05 cm/sec, 7.88E-04 cm/sec, and 3.89E-05 cm/sec, respectively.

LHSU groundwater typically flows under confined or semi-confined conditions, with only a few isolated areas of unconfined flow. Potentiometric maps of the LHSU were not constructed due to limited data. However, it is speculated that the LHSU potentiometric surface resembles that of the UHSU. Potentiometric data in LHSU wells suggest a general gradient toward the east. Recharge to the LHSU generally occurs in outcrop areas west of the Rocky Flats site and, to a limited degree, as downward seepage from the overlying UHSU. Discharge occurs primarily as downward seepage to the underlying units which is expected to be minimal due to the low permeabilities of the unweathered strata. The hydraulic conductivities (geometric mean) of the LHSU claystones, siltstones, and sandstones (2.48E-07, 1.59E-07, and 5.77E-07 cm/sec, respectively) are within the same order of magnitude, suggesting that groundwater flow remains relatively constant despite changes in lithology.

Surface-water/groundwater interactions at the Rocky Flats site generally respond to seasonal fluctuations in precipitation, recharge, groundwater storage, and stream and ditch flow. Drainages in the western and central areas of the Rocky Flats site are generally effluent during the spring. These gaining stretches may be enhanced where significant amounts of groundwater flow are available, such as in seep areas and/or in areas where surficial groundwater flow is controlled by incised bedrock paleochannels. Surface-water/groundwater interactions change significantly in drainages in the eastern part of the Rocky Flats site where influent conditions are predominant. Dam structures throughout the Rocky Flats site appear to impede downstream movement of groundwater in surficial deposits. Seeps generally occur on the upper margins of the drainages at the contact between the Rocky Flats Alluvium and bedrock unconformity. In addition, well hydrographs have demonstrated that historical spray evaporation activities in the south area of the East Spray Field provide a significant amount of recharge to the Rocky Flats Alluvium.

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List of Acronyms and Abbreviations

AIP	Agreement in Principle
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act
CDPHE	Colorado Department of Public Health and Environment
cfs	cubic feet per second
CLP	Contract Laboratory Program
cm/sec	centimeters per second
DOE	U.S. Department of Energy
EG&G	EG&G Rocky Flats, Inc.
EPA	U.S. Environmental Protection Agency
ERM	Environmental Restoration Management
ERPD	Environmental Restoration Program Division
°F	degrees Fahrenheit
FFCA	Federal Facilities Compliance Agreement
ft^2/day	square feet per day
GMP	Groundwater Monitoring Program
gpm	gallons per minute
IHSS	individual hazardous substance site
ITS	Interceptor Trench System
LHSU	lower hydrostratigraphic unit
mg/L	milligrams per liter
mph	miles per hour
NA	not available
NISC	National Information Services Corporation
NPDES	National Pollutant Discharge Elimination System
NPL	National Priorities List
NSL	New Sanitary Landfill
NTIS	National Technical Information Service
OU	operable unit
PVC	polyvinylchloride

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QA	quality assurance
QC	quality control
RCRA	Resource Conservation and Recovery Act
RFEDS	Rocky Flats Environmental Database System
RFETS	Rocky Flats Environmental Technology Site
RI	Remedial Investigation
SID	Southern Interceptor Ditch
SMOW	Standard Mean Ocean Water
TCE	trichloroethylene
TDS	total dissolved solids
TSS	total suspended solids
TU	tritium unit
UHSU	upper hydrostratigraphic unit
USGS	U.S. Geological Survey
VOC	volatile organic compound
WARP	Well Abandonment and Replacement Program
WWTP	Waste Water Treatment Plant

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Conversion Table

Length	1 in = 2.54 cm 1 ft = 0.3048 m
Volume	1 gal (US liquid) = 3.785 L = 0.1337 ft^3 = 3.785×10^{-3} m^3 = 3.068×10^{-6} acre-ft 1 ft^3 = 28.32 L = 7.481 gal = 2.832×10^{-3} m^3 = 2.296×10^{-5} acre-ft 1 acre-ft = 1233 m^3 = 1.233×10^{6} L = 3.259×10^{5} gal
Flow	1 ft^3/s = 2.832×10^{-2} m^3/s = 28.32 L/s = 448.8 gal/min 1 acre-ft/yr = 2.740×10^{-3} acre-ft/day = 0.62 gal/min = 3.913×10^{-2} L/s = 1.382×10^{-3} ft^3/s
Other	1 ft^2/d = 1.075×10^{-2} cm^2/s 1 cm/s = 2835 ft/day

1. Introduction

The Hydrogeologic Characterization Report was produced by the Environmental Restoration Program Division (ERPD) at the U.S. Department of Energy's (DOE's) Rocky Flats Environmental Technology Site (RFETS) as Volume II of the Sitewide Geoscience Characterization Study. The study was designed and directed by EG&G Rocky Flats, Inc. (EG&G) ERPD geosciences personnel. The report presents a comprehensive description of hydrogeology at Rocky Flats. The discussion of hydrogeology complements and supports the Geologic Characterization Report (Volume I) and Groundwater Geochemistry Report (Volume III) and provides a conceptual framework for discussions of groundwater occurrence and transport related to other sitewide and operable unit (OU) investigations.

1.1 Background

The Rocky Flats site (formerly called the Rocky Flats Plant) is located approximately 16 miles northwest of Denver, Colorado, in northern Jefferson County. The site occupies approximately 10 square miles; boundaries and major features are illustrated on Figure 1-1. Buildings are located within an industrial complex of approximately 400 acres (the Industrial Area) surrounded by a Buffer Zone of approximately 6,150 acres. Rocky Flats is a government-owned, contractor-operated facility that has been in operation since 1952. EG&G is the primary operating contractor.

Until January 1992, the Rocky Flats Plant was involved in manufacturing the plutonium component of nuclear weapons, reprocessing scrap metal and plutonium from dismantled weapons, conducting laboratory research on the properties of nuclear materials, and fabricating steel and beryllium components. In January 1992, the primary mission of the Rocky Flats site changed; the work force is now engaged in environmental restoration, waste management, decontamination and decommissioning, and economic development. In July 1994, the name of the Rocky Flats site was changed from Rocky Flats Plant to Rocky Flats Environmental Technology Site to reflect this change in mission.

Wastes produced during plant operations included hazardous wastes, low-level and transuranic radioactive wastes, and mixed wastes. Historically, these wastes have been either disposed onsite, stored in containers onsite, or disposed offsite. As a result of these past practices, Rocky Flats was proposed for inclusion on the Superfund National Priorities List (NPL) in 1984 and was included on the NPL in the October 4, 1989 *Federal Register*. Cleanup is being conducted under the Resource Conservation and Recovery Act (RCRA) and the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA). The U.S. Environmental Protection

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Agency (EPA) and the Colorado Department of Public Health and Environment (CDPHE) are the regulatory agencies overseeing the assessment and cleanup activities at 16 OUs on the site. Figure 1-2 illustrates current locations of the OUs at the Rocky Flats site.

Of the 16 OUs, one (OU3, Offsite Areas) is located outside site boundaries, one (OU15, Inside Building Areas) includes areas within buildings, and the remaining 14 are outside-of-building areas within site boundaries. Table 1-1 summarizes the general locations of the OUs, and the locations of individual hazardous substance sites (IHSSs) associated with OUs 1, 2, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, and 16 are shown on Figure 1-2. Areas within the OUs are discussed throughout this report.

1.2 Purpose and Scope

The Hydrogeologic Characterization Report provides a comprehensive characterization of site hydrogeology for use in OU-specific and sitewide studies. This report provides a conceptual model of groundwater flow and presents basic hydrogeologic data needed for future groundwater studies at the Rocky Flats site. The report describes previous hydrogeologic studies performed at Rocky Flats, the environmental setting of the site, regional hydrogeology, the hydrogeology of the Rocky Flats site, sitewide groundwater program activities, and recommendations for additional groundwater studies.

Sources of information used in the preparation of this report include the following:

- Published reports in the scientific literature and reports available from state and federal agencies
- Previous reports prepared by EG&G, Rockwell International, or their subcontractors, particularly the Well Evaluation Report (EG&G, 1994a), the 1993 Annual RCRA Groundwater Monitoring Report (EG&G, 1994b), and OU-specific reports
- Data collected as part of the continued Groundwater Monitoring Program
- The Geologic Characterization Report (Volume I, EG&G, 1995a)
- The Groundwater Geochemistry Report (Volume III, EG&G, 1995b)

In addition, information obtained from EG&G staff assigned to various OUs was used to supplement the technical reports and data.

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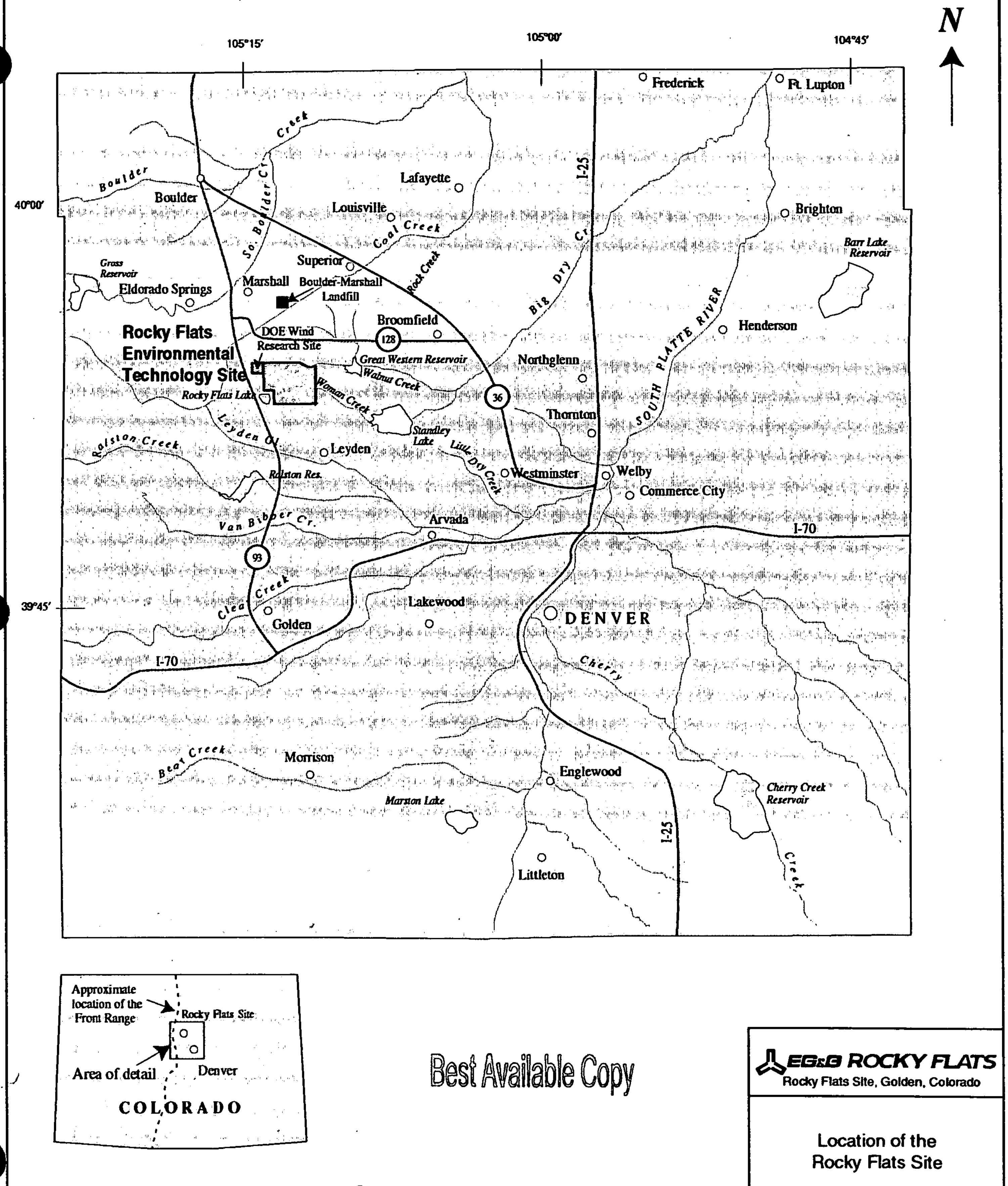
Table 1-1
Operable Units at the Rocky Flats Site

Operable Unit Number	Description	Number of IHSSs
OU1	881 Hillside	11
OU2	903 Pad, Mound, and East Trenches	20
OU3	Off-Site Releases	4
OU4	Solar Evaporation Ponds	1
OU5	Woman Creek	10
OU6	Walnut Creek	20
OU7	Present Landfill	2
OU8	700 Area	38
OU9	Original Process Waste Lines	1
OU10	Other Outside Closures	19
OU11	West Spray Field	1
OU12	400/800 Area	12
OU13	100 Area	15
OU14	Radioactive Sites	9
OU15	Inside Building Closures	8
OU16	Low-Priority Sites	7



Best Available Copy

EG&G ROCKY FLATS
Rocky Flats Site, Golden, Colorado

Location of the Rocky Flats Site

Hydrogeologic Characterization Report

April 1995 | Figure 1-1

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2. Review of Previous Hydrogeologic Studies

A search of historical records, reports, and documents was performed to identify sources of information related to the hydrogeology of the Rocky Flats site and vicinity. For each relevant document identified during this search, a brief description summarizing the purpose, information type, hydrogeological data presented, and conclusions of the study was prepared. Although some scientific documents identified were related to Rocky Flats in a regional sense only, summaries were prepared if the investigation made hydrogeological interpretations. Some reports identified as having relevance to Rocky Flats hydrogeology were included in the bibliography even though the documents could not be located. This comprehensive bibliography is included as Appendix A to this report.

2.1 Search Methods

The literature search was conducted using local libraries and reference systems. Reference sections of available documents were relied on for initial identification of pertinent documents. After locating the referenced documents, those document reference sections were referred to for further document identification and so on. Thereafter, the library or reference system databases (and card catalogs in some cases) were searched by topic using the word find commands. Hydrogeologic terms were used to search for pertinent documents, including words such as groundwater, hydrology, hydrogeology (and all of its expanded forms), water sampling, wells, Denver, Rocky Flats, environmental study, and others. In special libraries (e.g., Environmental Master File), entire years were searched as well as authors and specific known titles.

The bulk of documents directly related to Rocky Flats was easily accessible at the EG&G Rocky Flats, Inc., Environmental Library. Most topics not directly related to Rocky Flats, including U.S. Geological Survey (USGS) reports, maps, and investigations, were accessible at the USGS Library in Lakewood, Colorado. Some obscure and hard to find pertinent documents (i.e., personal memoranda, letters, meeting reports, historic investigation reports) were located in the Environmental Master File at Rocky Flats. The following libraries were searched:

- Denver Federal Center, U.S. Geological Survey Library
- EG&G Rocky Flats, Inc., Environmental Library
- EG&G Rocky Flats, Inc., Environmental Master File

- University of Colorado, Norlin Library and Department of Geological Sciences Library

- Front Range Community College, Rocky Flats Reading Room

- Colorado School of Mines, Arthur Lakes Library

- The S.M. Stoller Corporation, Environmental Services Library

At each library, the catalog system and the available reference databases (CD ROM format) were searched. At the EG&G library, the following databases were used:

- PLUS, Enviro/Energyline Abstracts
  Copyright 1993, Bowker Electronic Publishing

- National Technical Information Service (NTIS)
  NTIS Bibliographic Database, U.S. Department of Commerce
  Copyright 1987–1993, Silver Platter International N.V.

- National Information Services Corporation (NISC)
  Water Resources Abstracts
  Copyright 1991, 1993, Rom Wright

- NISC, Environmental Periodicals Bibliography
  Copyright 1972–June 1993, Rom Wright

- Dialog on Disc, Energy and the Environment Disc
  Copyright 1992–April 1993, Dialog Information Services, Inc.

At the USGS Library, the following additional databases were used:

- GEOREF
  Copyright 1990–1993, American Geological Institute, Silver Platter International N.V.

- Water Resources Abstracts, U.S. Department of the Interior
  U.S. Geological Survey
  Copyright 1991–1993, Silver Platter International N.V.

- Earth Sciences Disc. 1975–1992
  Earth Science Data Directory GEOINDEX
  Copyright 1992–1993, Silver Platter International N.V.

- Publications of the U.S. Geological Survey as of March 1993
  Copyrights: 1992, American Geological Institute
  1989–1992, I-MODE Retrieval Systems, Inc.

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1983–1992, Personal Library Software, Inc.

Documents and reports listed in CD ROM databases were often accompanied by an abstract. In cases where the abstract provided appropriate information, it was included within the prepared abstracts.

2.2 Abstracts and Bibliography

Documents and reports were reviewed to identify those that provided data or interpretations related to the hydrogeology at Rocky Flats. The pertinent documents and reports were further examined, and brief (approximately 100 to 250 words) summary descriptions were written. Each summary outlines the purpose, type of information, quantity of data, and significant conclusions and interpretations reached in the report.

Many of the unpublished documents and reports contain a variety of environmental data relating to the Rocky Flats site (e.g., biological, ecological, geological, geochemical). For documents that also contained hydrogeological information, the summaries were written to focus on the hydrogeological data, interpretations, and conclusions. Other reports that were not hydrogeologically oriented contained very general or brief hydrogeological reiteration of previous reports but offered no new interpretations and were not considered pertinent documents for purposes of this report. Several documents were identified during the search as possibly containing pertinent information but were not successfully located at the local libraries. The titles of these reports are included in Appendix A, but no summaries are presented.

3. Environmental Setting of the Rocky Flats Site and Surrounding Areas

The environmental setting is the basis for an understanding of the site hydrology and groundwater conditions. This section summarizes the hydrogeologic setting, including the climatology, vegetation, and surface-water hydrology, and includes useful background information for Section 4, Regional Hydrogeology, and Section 6, Hydrogeology of the Rocky Flats site.

3.1 Climatology

Climatologic information, including general descriptions of the climate, precipitation, temperatures, and wind patterns, is pertinent to the characterization of the hydrogeologic setting of the Rocky Flats site. Precipitation and temperature data are also provided for another station in the Denver area (Stapleton International Airport) for comparison. The Stapleton station was selected because it had the most complete record in the Denver metropolitan area.

Climatological data from Rocky Flats were obtained from one weather station where data (i.e., temperature, precipitation, wind direction and speed, atmospheric pressure, humidity, etc.) are collected by a datalogger. Both an instantaneous and average value are recorded at 15-minute intervals. The data are then transmitted to EG&G. Precipitation is measured using an automatic tipping bucket rain gage. Similar methods are employed for climatological data collection at Stapleton Airport; therefore, the Rocky Flats data are comparable to Stapleton data.

The Rocky Flats site is located in a semiarid climate, exhibiting wide daily temperature ranges and large seasonal temperature variations. Precipitation is low, primarily occurring in the spring. Rocky Flats is also characterized by high-wind events, most frequently in the winter months (EG&G, 1993a). The local climate at Rocky Flats influences groundwater conditions. For example, the amount and frequency of precipitation, combined with air temperatures and wind conditions, influence evapotranspiration and infiltration characteristics at the site. Many of these climatologic parameters are necessary components of a water balance or groundwater modeling effort. Climatologic values are summarized in the following sections.

3.1.1 Precipitation

Annual precipitation at Rocky Flats is nearly 15.5 inches, including rainfall and snowmelt. Nearly 42 percent of the annual precipitation falls from April through June. Precipitation falls primarily as snow from late October through early April. Summer precipitation results from showers and thunderstorms (EG&G, 1993a). Data for monthly total precipitation at Rocky Flats and Stapleton Airport in Denver for 1992 and 1993 are presented in Table 3-1 and Table 3-2, respectively. Comparison of the tables shows that Stapleton received approximately 1 inch more precipitation than Rocky Flats in 1992. Complete 1993 precipitation data for Stapleton are not available at this time. The mean total precipitation by month for the Rocky Flats site and Stapleton are provided in Figures 3-1 and 3-2, respectively. The general trends in precipitation are the same at both Rocky Flats and Stapleton with the greatest amounts of precipitation occurring during April, May, June, and July. At the Rocky Flats site, 36 percent of the precipitation occurs as snowfall (Table 3-3).

3.1.2 Air Temperatures

Characteristic of Colorado's Front Range, the climate at Rocky Flats is temperate and semiarid. The thin, dry atmosphere at the 6,000-foot elevation of the Rocky Flats site results in wide temperature ranges, with strong daytime warming and nighttime cooling (EG&G, 1993a). Temperature ranges, averages, and extreme temperature data for Rocky Flats in 1993 are presented in Table 3-4. Because the 1993 data are incomplete for Stapleton, temperature data for both 1992 and 1993 at Stapleton are presented in Table 3-5. Summaries of the historic temperature data at the Rocky Flats site and Stapleton are presented in Tables 3-6 and 3-7, and long-term average winter temperatures are presented in Tables 3-8 and 3-9, respectively. Mean daily temperatures were calculated by taking the average of the daily maximum and minimum. Mean monthly temperatures were calculated by taking the average of the mean daily temperatures throughout the month. Long-term averages were calculated by taking the average of the mean monthly temperatures throughout the year.

A comparison of Stapleton and Rocky Flats temperature data shows that winter nights are colder and winter days are warmer at Stapleton (Tables 3-8 and 3-9). During the spring, summer, and fall months, days are warmer at Stapleton; however, the minimum temperatures are approximately the same at Stapleton and the Rocky Flats site during these seasons (Tables 3-6 and 3-7).

3.1.3 Wind Patterns

High-wind events are common along the Front Range during the winter months. The Rocky Flats site normally experiences several days a year with peak wind gusts exceeding 60 miles per hour (mph); gusts reaching 80 mph or more occur less frequently (EG&G, 1993a). A summary of 1993 wind directions and wind-speed frequencies measured at a 10-meter height at the plant is provided in Table 3-10 and is shown graphically by a wind rose in Figure 3-3. Wind directions most frequently are from the west-southwest through northerly directions. Wind speeds above 18 mph

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occur primarily with westerly winds and, to a lesser extent, northerly winds (EG&G, 1993a).

3.1.4 Additional Climatological Information

Several additional climatological parameters are necessary for a comprehensive understanding of the hydrogeology of the site (Table 3-11). Pan evaporation data for the Denver metropolitan area show that evaporation is greatest during June, July, and August (Table 3-12). Total annual evaporation averages 166 centimeters (65.35 inches). Relative humidity is also measured at the Rocky Flats site. The average annual relative humidity at the site is 45.8 percent (Table 3-13).

3.2 Vegetation

The distribution of dominant plant species in a given geographic region often closely matches the underlying hydrology (Davis and DeWiest, 1966; Mitsch and Gosselink, 1986). Availability of water in the form of surface water, seeps and springs, or accessible groundwater provides an essential component for plant existence. However, flooding, intermittent flow, and saturated soils may also limit plant distribution to those species particularly adapted to these specific conditions.

These patterns are especially pronounced in ecosystems where water is limited. Such is the case in the area of the Rocky Flats site. The climate of this area is classified as semiarid (Clark, *et al.*, 1980). Perennial groundwater discharge from seeps and springs along drainages is an important augmentation to the limited surface-water runoff. Pools located along these drainages contain water even during periods of intermittent stream flow. A baseline biological characterization of the Rocky Flats site (DOE, 1992a) used soil moisture conditions to classify plant communities on the site: xeric, mesic, and hydric. Hydric soil moisture conditions occur in areas of intercepted groundwater flow near creek channels, hillside seeps, and springs at Rocky Flats. The locations, extent, and diversity of plant communities at the Rocky Flats site are in large part determined by the hydrology of the area. Availability of soil moisture is the most important factor affecting plant species diversity on the Rocky Flats site, with hydric areas exhibiting the highest diversity (Clark, *et al.*, 1980; DOE, 1992a). Many drought intolerant species and species specifically adapted to the conditions of saturated soils are located in hydric habitats, with most of the species present restricted to these areas of high soil moisture.

The Rocky Flats site Baseline Biological Characterization (DOE, 1992a) identified two major plant communities occurring in hydric soils at the Rocky Flats site: (1) riparian woodlands and (2) marsh (which includes wet meadows, short marsh, and tall marsh subdivisions). In addition, a minor tall upland shrub community type was identified as utilizing pockets of hydric soils within the more widespread mesic soil-moisture areas. A previous study of wetlands on the Rocky Flats site presents a list of many of the plant

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species located in these areas and their status as obligate or facultative wetland species (ASI, 1990).

3.2.1 Riparian Woodland Community

The riparian woodland community occurs in narrow strips located parallel to stream channels. The most prevalent vascular plants are riparian trees, plains cottonwood (*Populus deltoides*), and peachleaf willow (*Salix amygdaloides*), with an undergrowth of shade- and moisture-tolerant shrubs such as sandbar willow (*Salix exigua*), sedges, grasses, and herbs.

Parts of the riparian woodland are dominated by large stands of a snowberry (*Symphoricarpos* sp.) and Canada bluegrass (*Poa compressa*) association. Leadplant (*Amorpha fructosa*) may replace willow species in areas adjacent to stream channels, ditches, and ponds where more intermittent soil-moisture conditions occur or where the water table is lowered (DOE, 1992a).

The willow and cottonwood trees that dominate this riparian community are phreatophytes. These plants avoid much of the variation in water availability in arid environments by growing root systems that maintain constant contact with groundwater or the capillary fringe above the water table (Barbour *et al.*, 1987). Even in extremely arid zones, these plants may develop into large individuals. These types of plants are often the only trees that grow in arid grassland and desert areas and are a distinctive component of these ecosystems. As is found at the Rocky Flats site, phreatophytes are most usually found in streambeds and other locations where there are relatively shallow water tables. The cottonwood and willow trees at the Rocky Flats site are examples of obligate phreatophytes that adapted to a constant water supply. Shrubs such as leadplant are facultative phreatophytes that use groundwater when available but are also able to tolerate periods of low water availability.

Though phreatophytes are dependent on specific hydrological conditions, these plants have the potential to seriously affect the hydrology of an area. Because they also occur near a permanent source of water, these plants need not limit water use and often exhibit very little stomatal control. Therefore, these plants may have very high transpiration rates. In certain circumstances, this transpiration may be a significant source of groundwater discharge (Davis and DeWiest, 1966).

3.2.2 Marsh Community

The marsh community identified in the Baseline Biological Characterization (DOE, 1992a) includes wet meadows, short marsh, and tall marsh components. The wet meadows occur in moist, but not saturated, flat areas and are dominated by hydrophytic grasses such as prairie cordgrass (*Spartina pectinata*), sedges (*Carex* sp.), and rushes

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(*Juncus* sp.). Short marsh communities are limited to sites with soil that is seasonally saturated such as intermittent stream channels, seeps, and spring outflow areas. This marsh type has relatively low species diversity with few species of sedges and rushes. Tall marsh is strongly dominated by cattails (*Typha angustifolia* and *T. latifolia*) with some bulrushes (*Scirpus* sp.). These plants indicate the presence of persistent subsurface or standing water and commonly occur in valley bottoms and drainages and around ponds and surface-water impoundments. Patches of cattail marsh are also found on hillsides where perennial springs flow.

Hydrophytic plants that grow in marsh habitats must be adapted to root anoxia resulting from low oxygen levels and other chemical conditions in saturated soils. This significantly reduces the number of species that can survive in these marshes. Wetlands with minimum pore water flushing often result in low diversity as seen in the short marsh communities at the Rocky Flats site.

3.2.3 Tall Upland Shrub Community

The tall upland shrub community type is found in localized hydric microhabitats within mesic upland areas. These moister soils occur in shallow depressions where surface water may accumulate, on north facing slopes that retain snow cover, and in eroded areas where intermittent seeps occur. The higher moisture levels support a shrub community dominated by dense thickets of chokecherry (*Prunus virginiana*), wild plum (*Prunus americana*), and hawthorn (*Crateagus erythropoda*). Unlike the other hydric communities, plant species diversity is low in the tall upland shrub habitat. This is due to the dense cover of the dominant shrub shading out most herb and grass species. Though the intermittent availability of surface water and/or groundwater determine these habitats, plants that grow in them must also be adapted to accommodate the alkaline soil found in the surrounding mesic zone (DOE, 1992a).

3.3 Surface-Water Hydrology

This section characterizes the occurrence of surface water at and near the Rocky Flats site, including natural drainages, man-made ditches and diversions, and detention ponds. In preparation of this section, existing documents addressing surface water issues at the Rocky Flats site were reviewed. These documents include Draft Rocky Flats Surface Water Management Plan (EG&G, 1991a); The 1990 Surface Water and Sediment Geochemical Characterization Report (EG&G, 1992a); Final Phase I RFI/RI Work Plan - Woman Creek Priority Drainage (OU5) (DOE, 1992b); Final Work Plan Technical Memorandum Operable Unit No. 7 - Present Landfill and Inactive Hazardous Waste Storage Area (DOE, 1994c); Phase I RFI/RI Work Plan for Operable Unit 6 - Walnut Creek Priority Drainage (DOE, 1992b); a study of the Woman Creek Drainage (Fedors and Warner, 1993); and The Event Related Surface Water

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Monitoring Report, Rocky Flats Plant: Surface Water Years 1991 and 1992 (EG&G, 1993b).

3.3.1 Natural Drainages

Three drainage basins collect surface water at the Rocky Flats site. The basins are drained by natural, intermittent streams that generally flow from west to east. Maps showing the drainage basins, streams, and other surface-water features at the Rocky Flats site are presented in Figure 3-4 and Figure 3-5. The northwestern part of the Rocky Flats site is drained by Rock Creek, which eventually flows into Coal Creek east of the site. The Walnut Creek drainage basin traverses the western, northern, and northeastern areas of the plant, and the Woman Creek drainage basin collects water from the southern portion of the site (EG&G, 1992a). The following sections describe each of the drainage basins in detail.

Surface water in the natural drainages at the Rocky Flats site is typically a calcium-bicarbonate water, although sodium and chloride are often significant constituents at some locations (EG&G, 1992a). For a detailed review of surface-water chemistry at the Rocky Flats site, refer to the Event Related Surface Water Monitoring Report, Rocky Flats Plant: Surface-Water Years 1991 and 1992 (EG&G, 1993b) and the 1990 Surface Water and Sediment Geochemical Characterization Report (EG&G, 1992a).

3.3.1.1 Rock Creek Drainage Basin

The Rock Creek drainage basin is located entirely in the northwest Buffer Zone and has been maintained in a largely undisturbed state since the Rocky Flats site opened in 1952 (Figure 3-5). The portion of this basin on the Rocky Flats site (south of Colorado Highway 128) is approximately 2.9 square miles (1,660 acres) in area. A northeast-trending topographic divide separates the Rock Creek watershed from surface-water runoff in the Industrial Area leaving the drainage generally unaffected by operations at the site. Rock Creek flows to the northeast to its confluence with Coal Creek northeast of the Rocky Flats site boundary (EG&G, 1992a). Measurements taken during 1992 show that flow in Rock Creek at Colorado Highway 128 ranges from 0 cubic feet per second (cfs) to 8 cfs, with the greatest flows occurring during the spring months.

3.3.1.2 Walnut Creek Drainage Basin

The Walnut Creek drainage basin includes the western, northeastern, and northern portions of the Rocky Flats site. The Walnut Creek drainage basin is approximately 3.7 square miles (2,300 acres) in area and receives runoff from various site facilities, including most of the central portion of the Industrial Area. Three ephemeral streams drain the Walnut Creek watershed: No Name Gulch (commonly referred to as the unnamed tributary to Walnut Creek), North Walnut Creek, and South Walnut Creek.

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These streams converge in the eastern part of the Buffer Zone to form Walnut Creek. Walnut Creek then flows to the east toward Great Western Reservoir where it is diverted around the reservoir by the Broomfield Diversion Ditch (EG&G, 1992a). Flows measured at Walnut Creek and Indiana Street during 1992 range from 0 cfs to 11 cfs, with the greatest flows occurring during the spring months (EG&G, 1993b).

No Name Gulch is the northernmost tributary to Walnut Creek. The existing landfill and landfill pond (OU7) are sited within the channel of No Name Gulch. The landfill pond has not discharged water to No Name Gulch because the water level in the pond was historically controlled by spray evaporation (EG&G, 1995a).

Flow in North Walnut Creek is affected by several engineered structures including a surface-water diversion structure that diverts water from North Walnut Creek and a series of detention ponds known as the A-series ponds. Water from the upper reaches of North Walnut Creek is currently diverted to the McKay Bypass and flows north of the landfill and north of the A-series ponds. The water is eventually returned to North Walnut Creek downstream of Pond A-4. Surface-water flow along the reach of North Walnut Creek below the McKay Bypass diversion structure is diverted via pipeline around Ponds A-1 and A-2 and discharged in Pond A-3. Ponds A-1 and A-2 are presently used for control of spill releases within the Industrial Area and do not discharge to the creek. Water in Pond A-3 is released to Pond A-4, which is then tested, treated if necessary, and discharged to North Walnut Creek in accordance with the National Pollutant Discharge Elimination System (NPDES) permit, the Federal Facilities Compliance Agreement (FFCA), and the Agreement in Principle (AIP) (EG&G, 1991a).

The headwaters of South Walnut Creek are located in the center of the Industrial Area. South Walnut Creek receives stormwater runoff from the Industrial Area including water from the main drainage ditch along Central Avenue. The natural channel of South Walnut Creek has been significantly changed by construction. The B-series detention ponds were constructed in the channel of South Walnut Creek to control the flow of surface water. Currently, flow is diverted around Ponds B-1, B-2, and B-3 to Pond B-4. Pond B-4 has limited storage capacity, and water typically flows into Pond B-5 as well. Pond B-3 currently receives effluent from the sewage treatment plant via pipeline. Water is discharged from Pond B-3 to Pond B-4 and, subsequently, Pond B-5 in accordance with the Rocky Flats site NPDES permit. Water from Pond B-5 is transferred via pipeline to Pond A-4 where it is tested, treated if necessary, and discharged to Walnut Creek in compliance with the NPDES permit, the FFCA, and the AIP (EG&G, 1991a). Ponds B-1 and B-2 contain runoff from the local slope and do not discharge to the creek.

3.3.1.3 *Woman Creek Drainage Basin*

The Woman Creek drainage basin is located in the southern part of the Rocky Flats site. The portion of the Woman Creek drainage basin west of Indiana Street is approximately 3.1 square miles (2,000 acres) in area within the Rocky Flats site (EG&G, 1992). In the western Buffer Zone, Woman Creek has two branches known as the northwest branch and southwest branch. The northwest channel receives water from precipitation, leaks in the Boulder Diversion Ditch crossover structure, groundwater, and Kinnear Ditch. The southwestern branch of Woman Creek receives water primarily from Rocky Flats Lake via Smart Ditch #2. The two branches of Woman Creek converge approximately 1.5 miles east of Colorado Highway 93 (Fedors and Warner, 1993).

Two detention ponds are present in the Woman Creek drainage basin: Pond C-1 and Pond C-2. The Southern Interceptor Ditch (SID) collects runoff from the areas south of OU1 and OU2. The intercepted water is routed to Pond C-2 and is diverted to Pond A-4 where it is eventually pumped, treated, and discharged to Walnut Creek. The other detention pond along Woman Creek, Pond C-1, has a limited capacity and is presently used only for flow measurements (EG&G, 1991a).

As Woman Creek flows to the east, it is diverted around Pond C-2 and returns to the natural channel for only a short distance before being diverted into Mower Ditch by an earthen dam. Mower Ditch supplies water to Mower Reservoir which is located southeast of the site. Limited amounts of water appear to be seeping through this earthen dam and into the natural drainage. The water in Woman Creek also occasionally spills over the Mower Ditch diversion structure and into the natural drainage during high-flow periods. The water that passes through or over the dam flows east into Standley Lake along with water collected by Woman Creek downgradient of the Mower Ditch diversion structure (Fedors and Warner, 1993).

The magnitude of flow in Woman Creek varies seasonally. Measurements taken during 1992 in Woman Creek at Indiana Street indicate that flow varies from 0 cfs to 8 cfs. Typically the highest flows are measured in the spring months, and much of the creek is dry during late summer, fall, and winter. Flow in Mower Ditch at Indiana Street varied from 0 to 4 cfs downstream during 1992 (EG&G, 1993b). The flow in Mower Ditch appears to be related to the resupply of irrigation water to Mower Reservoir. Surface-water/groundwater interactions are discussed in greater detail in Section 6.5.

3.3.2 Ditches and Diversions

Several ditches and diversion canals transport water through and around the Rocky Flats site. The Upper Church, McKay, Smart, and Mower ditches cross the site. The Last Chance Ditch flows immediately south of the site boundary, and the South

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Boulder Diversion flows west of the site parallel to Colorado Highway 93. Upper Church, McKay, Kinnear, and Last Chance ditches divert water from Coal Creek at locations west of the site. Upper Church and McKay ditches are used to transport water to Great Western Reservoir, and Kinnear Ditch is used to deliver water to Woman Creek. The Last Chance Ditch diverts water to Rocky Flats Lake and Standley Lake. The South Boulder Diversion diverts water from South Boulder Creek to Ralston Reservoir and supplies raw water to the Rocky Flats site (EG&G, 1992a).

Smart Ditch #2, located in the southwest Buffer Zone, supplies water to Woman Creek from Rocky Flats Lake, and Smart Ditch #1 transports water from Rocky Flats Lake offsite to the east. Mower Ditch diverts water from Woman Creek to Mower Reservoir located immediately east of Indiana Street (EG&G, 1992a).

Additional diversions not described above include the Woman Creek Diversion Canal around Pond C-2; the diversion in North Walnut Creek around Ponds A-1 and A-2; and the diversion in South Walnut Creek around Ponds B-1, B-2, and B-3. The West Diversion Canal was constructed to divert water from the Building 130 area to the McKay Bypass Canal. The McKay Bypass Canal is used to divert water from McKay Ditch and the western part of North Walnut Creek around the A-series ponds (EG&G, 1992a).

Table 3-1
Total Precipitation at the Rocky Flats Site, 1992 and 1993

Monthly Totals (inches)	1992	1993
January	0.31	0.13
February	0.02	0.54
March	3.37	1.52
April	0.53	1.45
May	1.53	1.13
June	2.19	1.79
July	1.30	0.48
August	2.97	0.42
September	0.00	1.58
October	0.59	1.41
November	1.25	1.27
December	0.43	0.35
Total (inches)	**14.49**	**12.07**

Table 3-2
Total Precipitation at Stapleton International Airport, 1992 and 1993

Monthly Totals (inches)	1992	1993
January	1.19	0.25
February	0.09	1.05
March	3.50	0.89
April	0.53	2.08
May	1.13	0.93
June	2.02	1.67
July	2.23	NA
August	2.33	NA
September	0.01	NA
October	0.51	NA
November	1.46	NA
December	0.68	NA
Total (inches)	**15.68**	**6.87**

NA: Not Available

Table 3-3
Percentage of Precipitation as Snow at the Rocky Flats Site

	Total Precipitation (inches)	Snow Water Equivalent (inches)	Percent Precipitation as Snow
1964	6.64	2.44	37%
1965	18.87	4.96	26%
1966	11.40	6.25	55%
1967	22.54	4.35	19%
1968	12.71	5.30	42%
1969	24.71	8.13	33%
1970	18.79	5.87	31%
1971	14.30	6.25	44%
1972	14.78	8.82	60%
1973	21.55	7.24	34%
1974	13.77	3.25	24%
1975	12.04	3.40	28%
1976	13.51	5.20	38%
1986	14.47	5.20	36%
1989	15.76	4.12	26%
1990	NA	4.30	NA
1991	NA	3.50	NA
1992	12.33	5.40	44%
1993	12.07	5.20	43%
Average	**15.31**	**5.22**	**36%**

NA: Not Available

Table 3-4
Temperature Data for the Rocky Flats Site, 1993

	Means (°F)		
	High	Low	Average
January	38	18	28
February	32	17	24
March	48	28	38
April	54	31	42
May	65	42	54
June	73	48	60
July	80	54	67
August	75	54	65
September	69	49	59
October	59	32	46
November	45	20	32
December	46	21	33
Average	**57**	**34**	**46**

	Extremes (°F)			
	High	Date	Low	Date
January	56	22, 27	-4	10
February	53	19	-10	16
March	67	25	5	13
April	68	22	22	12
May	82	26	28	1
June	90	15	35	4
July	91	10, 29	49	5, 7
August	87	24	43	30
September	85	11	31	13
October	83	6	1	30
November	64	10	-10	25
December	60	26	-5	22
Extreme	**91**	**7/10, 7/29**	**-10**	**2/16, 11/25**

Table 3-5
Temperature Data for Stapleton International Airport, 1992 and 1993

	Means (°F)		
1992	High	Low	Average
January	45	18	32
February	53	28	40
March	55	31	43
April	69	40	55
May	74	47	61
June	79	53	66
July	84	57	71
August	82	54	68
September	81	49	65
October	70	37	54
November	46	22	34
December	39	12	25
Average	**65**	**37**	**51**

	Extremes (°F)			
1992	High	Date	Low	Date
January	66	31	-5	15
February	70	29	21	5, 19, 24
March	67	15, 27	8	10
April	90	30	26	1
May	87	1, 18	40	4, 29
June	94	30	41	2
July	99	6	50	2, 3
August	95	9	48	26, 27
September	90	11	38	26
October	86	3, 1	23	8
November	70	15	8	25, 28
December	60	11	-4	19
Extreme	**99**	**7/6**	**-5**	**1/15**

	Means (°F)		
1993	High	Low	Average
January	39	15	27
February	41	18	29
March	55	30	43
April	62	35	48
May	73	45	59
June	81	52	66
July	NA	NA	NA
August	NA	NA	NA
September	NA	NA	NA
October	NA	NA	NA
November	NA	NA	NA
December	NA	NA	NA
Average	**58**	**33**	**45**

	Extremes (°F)			
1993	High	Date	Low	Date
January	61	27	-5	10
February	59	6	-9	17
March	74	23, 25, 2	10	13
April	82	22	28	4
May	86	26	30	2
June	98	29	44	4
July	NA	NA	NA	NA
August	NA	NA	NA	NA
September	NA	NA	NA	NA
October	NA	NA	NA	NA
November	NA	NA	NA	NA
December	NA	NA	NA	NA
Extreme	**98**	**6/29**	**-9**	**2/17**

NA: Not Available

Table 3-6
Historic Monthly Temperature Data for the Rocky Flats Site

	Means (°F)			Extremes (°F)	
	High	Low	Average	High	Low
January	41	22	32	69	-12
February	42	24	33	71	-10
March	49	28	38	82	-5
April	58	36	47	80	13
May	64	43	54	89	6
June	76	55	65	99	35
July	82	60	71	102	44
August	80	58	69	97	38
September	70	50	60	91	24
October	61	40	50	83	0
November	49	31	40	71	-10
December	42	24	33	72	-8
Average / **Extreme**	**59**	**39**	**49**	**102**	**-12**

Table 3-7
Historic Monthly Temperature Data for Stapleton International Airport

	Means (°F)			Extremes (°F)	
	High	Low	Average	High	Low
January	43	16	30	73	-25
February	47	21	34	76	-25
March	52	26	39	84	-8
April	61	34	48	90	-2
May	71	44	57	93	22
June	82	53	67	102	30
July	88	59	73	103	43
August	86	57	71	100	41
September	77	48	63	97	17
October	67	37	52	89	3
November	52	25	39	79	-8
December	45	18	32	75	-25
Average / **Extreme**	**64**	**37**	**50**	**103**	**-25**

Table 3-8
Long-Term Average Winter* Temperatures at the Rocky Flats Site

	High (°F)	Low (°F)	Average (°F)
1965	46	26	NA
1966	46	30	38
1971	45	25	35
1972	37	21	29
1973	44	26	35
1974	45	27	36
1986	44	27	36
1987	43	26	34
Average	**44**	**26**	**35**

*Winter is defined as November, December, January, and February.

NA: Not Available

Table 3-9
Long-Term Average Winter* Temperatures at Stapleton International Airport

	High (°F)	Low (°F)	Average (°F)
1948	41	15	28
1949	52	22	37
1950	48	21	34
1951	47	21	34
1952	47	22	34
1953	53	25	39
1954	47	20	33
1955	46	20	33
1956	48	22	35
1957	50	24	37
1958	47	21	34
1959	45	19	32
1960	46	20	33
1961	41	15	28
1962	47	18	33
1963	47	17	32
1964	47	21	34
1965	49	19	34
1966	50	21	36
1967	47	18	33
1968	48	19	34
1969	50	20	35
1970	48	19	34
1971	50	19	34
1972	42	18	30
1973	46	19	32
1974	47	19	33
1975	50	22	36
1976	50	21	36
1977	46	21	33
1978	41	16	29
1979	44	20	32
1980	54	25	39
1981	49	23	36
1982	45	22	34
1983	40	17	29
1984	44	18	31
1985	46	21	34
1986	47	22	35
1987	44	19	32
1988	45	19	32
1989	48	22	35
1990	48	21	34
1991	47	22	35
1992	41	17	29
Average	**47**	**20**	**34**

*Winter is defined as November, December, January, and February

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Table 3-10
Wind Speed and Wind Direction at the Rocky Flats Site, 1993

	Wind Speed (mph)	
	Mean	Peak
January	9	75
February	7	70
March	9	50
April	9	67
May	8	60
June	9	58
July	9	73
August	8	47
September	8	58
October	8	66
November	10	66
December	12	82
Annual	**9**	**82**

Wind Direction Frequency	
Direction	Percent
Calm	2.7
N	7.7
NNE	6.1
NE	4.7
ENE	3.6
E	3.6
ESE	3.8
SE	5.4
SSE	5.7
S	5.2
SSW	4.6
SW	5.2
WSW	6.4
W	8.4
WNW	11.7
NW	7.7
NNW	7.4
	100.0

Table 3-11
Climatic Summary—Rocky Flats Site

	1993	Long-Term Average
Mean Dew Point (°F)	26	31
Mean Relative Humidity (%)	41	46
Mean Atmospheric Pressure (mb)	812	816
Solar Total (kW h/m^2)	166	Not Available

Table 3-12
Approximate Pan Evaporation in Denver
(1931–1960)

	Evaporation (cm)
January	0
February	0
March	10
April	17
May	20
June	24
July	29
August	30
September	22
October	14
November	0
December	0
Annual Evaporation	**166**

Source: EPA, 1983, Hazardous Waste Land Treatment, SW-874: Municipal Environmental Research Laboratory, Office of Research and Development, Cincinnati, Ohio.

Table 3-13
Average Relative Humidity at the Rocky Flats Site
(1972–1977, 1985–1989, 1993)

	Average Relative Humidity (%)
January	46.5
February	47.5
March	48.7
April	52.0
May	45.4
June	42.0
July	43.5
August	39.2
September	44.0
October	42.5
November	52.4
December	46.0
Average	**45.8**

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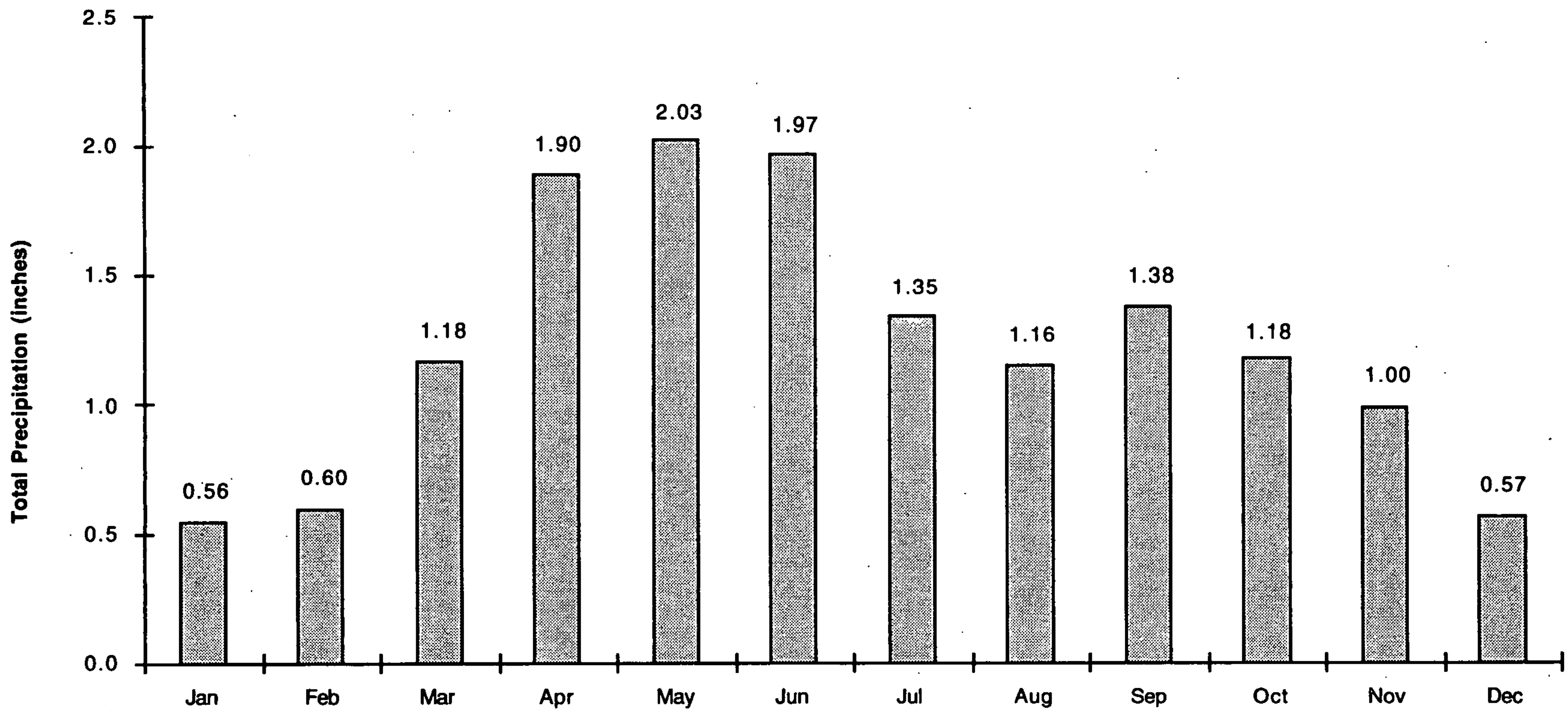

EG&G ROCKY FLATS

Rocky Flats Site, Golden, Colorado

Historic Mean Total Precipitation at the Rocky Flats Site

Hydrogeologic Characterization Report

April 1995	Figure 3-1

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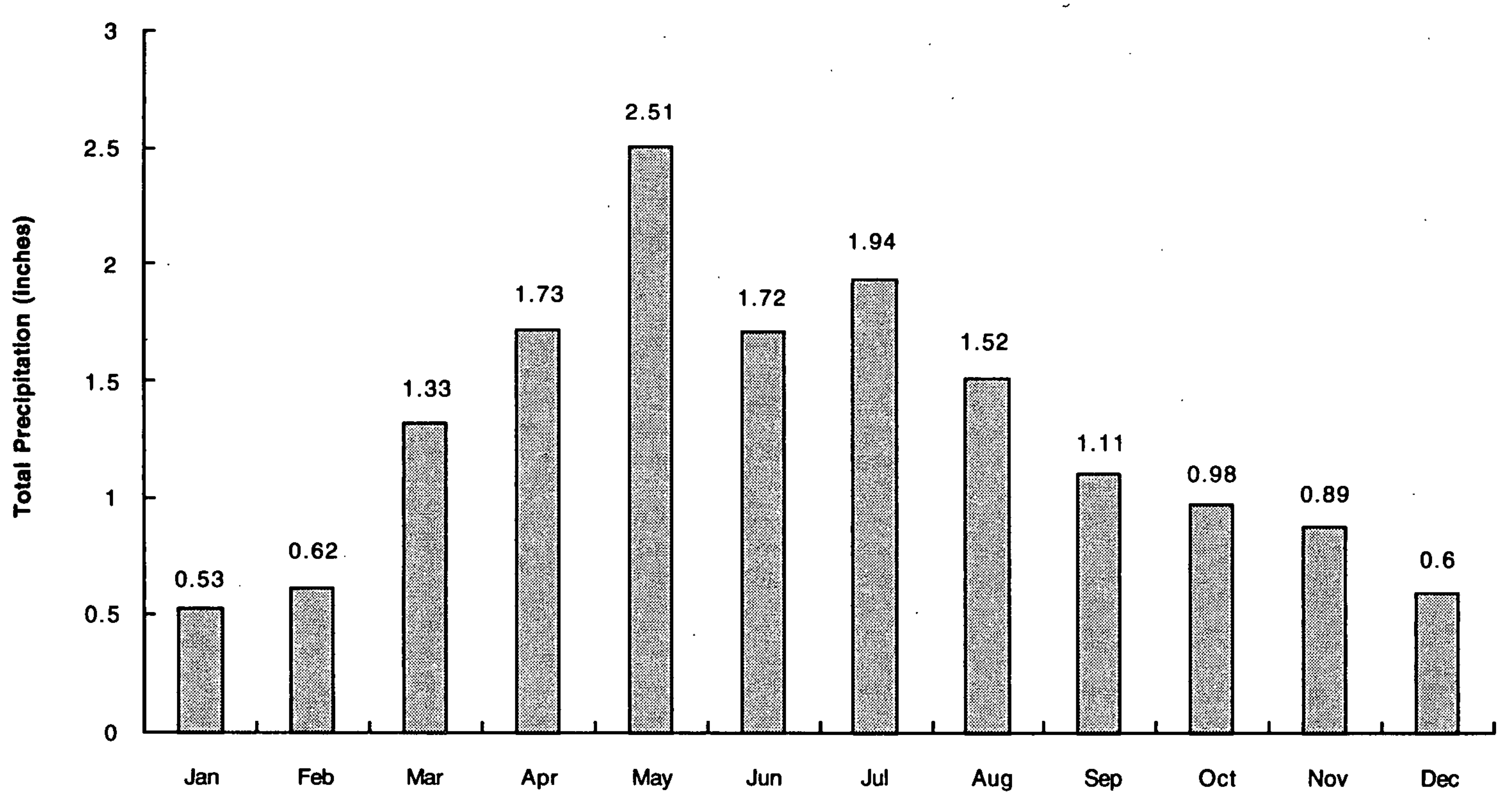

EG&G ROCKY FLATS

Rocky Flats Site, Golden, Colorado

Historic Mean Total Precipitation at Stapleton International Airport

Hydrogeologic Characterization Report

April 1995	Figure 3-2

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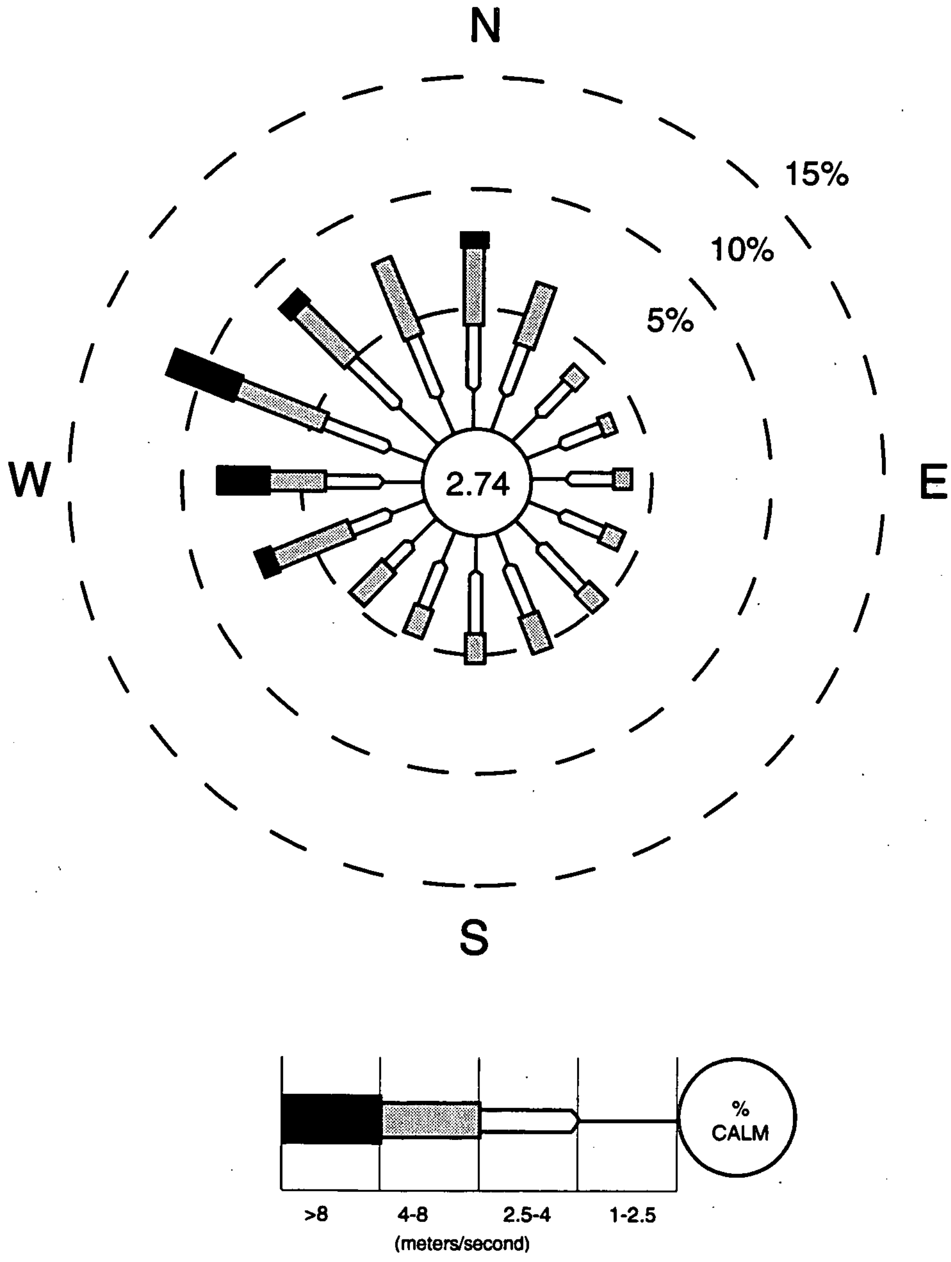

EG&G ROCKY FLATS

Rocky Flats Site, Golden, Colorado

Wind Rose (24-hour)
for the Rocky Flats Site, 1993

Hydrogeologic Characterization Report

April 1995	Figure 3-3

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4. Regional Hydrogeology

Groundwater at the Rocky Flats site reflects local hydrogeologic conditions unique to the facility as well as hydrogeologic conditions that occur at the regional scale of the Denver structural basin. To understand the groundwater flow system at Rocky Flats, it is important to recognize both local and regional conditions. Rocky Flats overlies a regional aquifer system called the Denver groundwater basin. A brief description of this aquifer system is provided in Section 4.1 of this report. Hydrogeologic conditions within the northwest part of the regional aquifer system are particularly relevant to an understanding of the hydrogeology at Rocky Flats. Therefore, this part of the regional aquifer system is characterized in Sections 4.2 through 4.6, with particular emphasis on the relationship of groundwater at Rocky Flats to regional flow patterns.

4.1 Hydrogeology of the Denver Groundwater Basin

The Denver groundwater basin underlies approximately 6,700 square miles extending from the Front Range of the Rocky Mountains east to Limon and from Greeley south to near Colorado Springs (Figure 4-1, also refer to Figure 1-1 for geographic references discussed in Section 4). Rocky Flats is located on the northwest margin of the basin. Land-surface altitudes in the basin range from 4,500 feet on the northeast to 7,500 feet on the south. Except for the extreme southern part of the basin, surface drainage is toward the north and northeast. Mean annual precipitation is related to altitude and ranges from 11 inches along the northeast margin of the basin to 18 inches along the southern margin. A number of perennial streams including the South Platte River and Clear Creek originate in the Front Range and flow across the northwest part of the Denver groundwater basin. These streams and associated irrigation diversions are important sources of water for aquifers in the Denver groundwater basin.

The water resources of the Denver groundwater basin are used extensively. As a result, a large number of hydrologic investigations have been conducted to characterize the regional aquifer system. Comprehensive descriptions of the basin are provided by Romero (1976), Hillier *et al.* (1983a), and Robson (1987). Much of the information provided in this section of the report was obtained from these references. Additional information was obtained as referenced elsewhere in the text.

4.1.1 Hydrogeologic Units

The Denver groundwater basin consists of a series of regional aquifers within water-yielding strata of the Fox Hills Sandstone, Laramie Formation, Arapahoe Formation, Denver Formation, Dawson Arkose, and Quaternary alluvial deposits. These formations attain a maximum thickness of 3,200 feet in an area about 50 miles south of

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Denver. Total thickness of sediments exceeds 1,000 feet over approximately half the Denver basin. Water-yielding deposits consist of silt, sand, and gravel beds with a net thickness that rarely exceeds one-third of the total thickness of all sediments in the Denver groundwater basin. Water-yielding deposits occur as beds with limited areal extent. Individual bed thickness rarely exceeds 100 feet and typically is much less. A comprehensive description of the lateral and vertical distribution of water-yielding materials is provided in the Geologic Characterization Report (EG&G, 1995a). Aquifers in the Denver groundwater basin are defined where the hydraulic connection of water-yielding materials in both vertical and lateral directions is sufficient for the strata to respond as a single hydrostratigraphic unit.

Five regional aquifers have been identified in the Denver groundwater basin. In ascending order, the aquifers are termed the Laramie/Fox Hills aquifer, the Arapahoe aquifer, the Denver aquifer, the Dawson aquifer, and the regional alluvial aquifer. With the exception of the Denver and Dawson aquifers, all are present at Rocky Flats. However, the Denver aquifer is present approximately 7 miles southeast of Rocky Flats and has an influence on groundwater movement in the northwest part of the Denver groundwater basin. The Dawson aquifer is present only in the southern part of the basin and has no effect on groundwater movement in the vicinity of Rocky Flats.

The Pierre Shale underlies the Fox Hills Sandstone and is considered to be the base of the water-yielding units of the Denver groundwater basin. Thickness of the Pierre Shale exceeds 5,000 feet, and permeability is minimal.

The Laramie/Fox Hills aquifer is the deepest and most extensive aquifer in the basin. The aquifer occurs primarily in the upper sandstone and siltstone sequence of the Fox Hills Sandstone and the lower sandstone units of the overlying Laramie Formation. In the area northwest of Denver, the upper 100 to 200 feet of the Pierre Shale includes sandstones. The uppermost of these sandstones are likely to be hydraulically connected to those of the Fox Hills Sandstone and are considered to be part of the Laramie/Fox Hills aquifer. Total thickness of water-yielding material in the Laramie/Fox Hills aquifer typically is 100 to 200 feet with no pronounced regional trends. The water-yielding material is predominantly very fine-grained to medium-grained sandstone with interstitial silt and clay. A shale bed of 5 to 20 feet generally separates the Laramie and Fox-Hills sections of the aquifer.

In the northwest part of the basin, numerous northeast-trending faults have offset strata of the Laramie/Fox Hills aquifer. Locations of some faults have been mapped (Colton and Lowrie, 1973). Noting large differences in water-level altitudes in wells, Schneider (1980) suspected that these faults may function within the Laramie/Fox Hills aquifer as barriers to horizontal water movement. Faulting near the Boulder-Marshall Landfill (T1S, R70W, Sec. 22 and Sec 23) has placed claystones of the upper Laramie

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Formation against sandstones of the Laramie/Fox Hills aquifer and significantly restricted lateral flow (Fox Consultants, 1984). Noting the predominant northeast trend of topographic features between Boulder Creek and the South Platte River, Robson (1987) suggested that additional northeast-trending faults may be present. The Geologic Characterization Report (EG&G, 1995a) provides a comprehensive description of suspected faulting at Rocky Flats.

The upper part of the Laramie Formation forms a confining unit that overlies the Laramie/Fox Hills aquifer. The confining unit consists of gray to black claystone, coal, and minor amounts of siltstone and sandstone. Throughout much of the Denver groundwater basin, the confining unit is 400 to 500 feet thick. However, at Rocky Flats, well records indicate that the unit may be as much as 800 to 900 feet thick. Local aquifers may occur in the upper part of the Laramie Formation where sufficient sandstone is present or where fracturing is extensive. However, regionally, the upper part of the Laramie Formation is considered a confining unit.

The Arapahoe aquifer consists of a thick sequence of interbedded conglomerate, sandstone, siltstone, and shale. In the northern part of the Denver groundwater basin, shale is more prevalent and sometimes divides the aquifer into upper and lower parts, each with a thickness of 150 to 200 feet. Where present, the middle section consists of relatively homogeneous shale with a thickness of about 100 feet. Total thickness of the Arapahoe aquifer typically ranges from 500 to 700 feet. However, only 200 to 300 feet of water-yielding material is generally present. Thickness of water-yielding material decreases to less than 100 feet along basin margins. Individual sandstone and conglomerate beds generally are lenticular and limited in areal extent. The hydraulic properties of the aquifer depend regionally on the dimensions and spatial frequency of the individual beds. In the central part of the basin, the beds are closely spaced and form a single hydrostratigraphic unit that is 200 to 300 feet thick in places. The Arapahoe aquifer is very thin and consists of the Arapahoe Formation sandstone at Rocky Flats.

The Denver aquifer consists of interbedded shale, claystone, siltstone, and sandstone. Beds of coal and fossilized plant remains are common. The Denver aquifer is distinguished from the underlying Arapahoe aquifer and overlying Dawson aquifer by a generally darker color, the presence of coal, and the predominance of shale and claystone over more permeable rock types. Total thickness of the Denver aquifer is typically 600 to 1,000 feet. However, thickness of water-yielding material generally is less than 250 feet. The water-yielding layers of sandstone and siltstone generally occur as irregular lenses that are widely dispersed within relatively thick sequences of claystone and shale. The Denver aquifer is not present at Rocky Flats but occurs about 7 miles southeast of the facility.

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The Dawson aquifer occurs only in the southern half of the Denver groundwater basin and has no effect on regional flow patterns in the vicinity of the Rocky Flats site. Where present, the Dawson aquifer consists of coarse-grained conglomerate and sandstone with interbedded shale. The thickness of water-yielding material typically is 100 to 400 feet.

The regional alluvial aquifer consists of a widespread but discontinuous cover of unconsolidated sand and gravel with varying amounts of silt and clay. The aquifer includes present-day stream flood-plain deposits, unconsolidated deposits along several ancestral stream channels, and a series of alluvial terrace deposits. A broad area of wind-blown sand located east of the South Platte River and derived mainly from alluvium of major streams is included within the alluvial aquifer. In general, geologically younger terraces such as the Piney Creek Alluvium and the Broadway Alluvium are laterally continuous and hydraulically connected to flood-plain alluvium along present-day and ancestral stream valleys. Geologically older terraces including the Louviers Alluvium, Slocum Alluvium, Verdos Alluvium, and Rocky Flats Alluvium are elevated topographically from the streams. In many locations the Verdos Alluvium and Rocky Flats Alluvium tend to be preserved as isolated remnants. Hydraulic connection of these remnants with the alluvial aquifer along streams is possible only through groundwater movement in the bedrock aquifers or by discharge to seeps and small tributary streams. Rocky Flats is located on a large isolated remnant of the Rocky Flats Alluvium.

The water-yielding characteristics of the alluvial aquifer depend on the saturated thickness and transmissive nature of the sediments. Saturated thickness of more than 100 feet occurs along the South Platte River downstream of Greeley. Thickness of more than 50 feet occurs along the South Platte River downstream of Denver and along the lower reaches of Box Elder Creek, Kiowa Creek, and Bijou Creek. The saturated thickness of isolated terraces of Verdos and Rocky Flats Alluvium typically is less than 20 feet. Seasonal fluctuations in saturated thickness can be large within the isolated terraces, in response to variations in recharge, and at many locations the alluvium periodically becomes unsaturated. Coarse sand, gravel, and cobbles tend to dominate alluvial sediments along Clear Creek, Bear Creek, and the upper portion of the South Platte River, resulting in high well yields. Highly transmissive sand predominates in the alluvium along the principal streams and creeks east of the South Platte River. Sand, silt, and clay compose the sediments of smaller tributaries, and well yields are correspondingly smaller. Sediments of the Verdos Alluvium and Rocky Flats Alluvium follow a trend similar to that of other alluvial deposits with bouldery cobbles and gravel near the mountains decreasing in size away from the mountains. However, well yields tend to be smaller than might be expected due to a much larger percentage of silt and clay than occurs in deposits along streams.

4.1.2 Aquifer Characteristics

The ability of an aquifer to transmit water depends on the thickness and permeability of the water-yielding material. Hydraulic conductivity is used to measure the ability of a unit volume of aquifer to transmit water and is estimated by conducting aquifer tests and laboratory analysis and by developing numerical models of groundwater flow. Combined with descriptions of hydraulic gradient and effective porosity, hydraulic conductivity is also used to estimate rates of groundwater flow and mass transport. Transmissivity is the product of hydraulic conductivity and saturated thickness and is useful in determining the water-yielding characteristics of an aquifer. Another measure of the water-yielding characteristics of an aquifer is the storage coefficient or, in water-table aquifers, the specific yield. These aquifer characteristics measure the ability of an aquifer to store water and depend on thickness and porosity. The storage coefficient for an aquifer under confined pressure also depends on the compressibility of the water and rock matrix.

The hydraulic conductivity of the Denver groundwater basin has been reported by Robson (1983). Hydraulic-conductivity values of the Laramie/Fox Hills aquifer range from more than 6 feet/day (2.1E-03 cm/sec) near Littleton to less than 0.05 feet/day (1.8E-05 cm/sec) along the northwest margin of the aquifer where Rocky Flats is located. Robson (1983) also reported values as large as 7 feet/day (2.5E-03 cm/sec) for the Arapahoe aquifer south of Littleton; however, values less than 0.5 feet/day (1.8E-04 cm/sec) were reported for the central part of the Arapahoe aquifer. Values of hydraulic conductivity obtained from aquifer tests of the Arapahoe aquifer at Rocky Flats are consistent with these estimates and are presented later in this report. Hydraulic conductivity of the Denver aquifer ranges from 0.5 to 1.5 feet/day (1.8E-04 to 5.3E-04 cm/sec); the Dawson aquifer ranges from 0.2 to 3.0 feet/day (7.1E-05 to 1.1E-03 cm/sec).

Transmissivity of the bedrock aquifers also was mapped by Robson (1983). These estimates were used as a basis for a regional model of groundwater flow (Robson, 1987). Transmissivity ranges from zero at the edge of each aquifer to more than 1,000 ft^2/day in the Laramie/Fox Hills aquifer; 2,100 ft^2/day in the Arapahoe aquifer; 400 ft^2/day in the Denver aquifer; and 1,200 ft^2/day in the Dawson aquifer. Simulations with a regional groundwater flow model (Robson, 1987) indicated that northeast-trending faults in the Laramie/Fox Hills aquifer may extend through much of the area north of Westminster and west of Brighton. By including an anisotropy ratio of 25 to simulate the regional hydrologic effects of faulting in this area, simulation results showed significant improvement. Robson noted that the model grid was not aligned with the fault orientation, effectively decreasing model reliability in the faulted area.

Hurr and Schneider (1972) and Robson (1989) reported the transmissivity of the alluvial aquifer. Transmissivity of the alluvial aquifer is strongly influenced by saturated thickness but also is affected by changes in hydraulic conductivity. Along the South Platte River, saturated thickness of the alluvial aquifer increases and hydraulic conductivity decreases from Denver toward Greeley and Fort Morgan. However, the thickness effects are more pronounced, resulting in a general downstream increase in transmissivity. Downstream from Greeley, transmissivity averages about 13,000 ft^2/day. Upstream, the transmissivity decreases but remains several orders of magnitude higher than the transmissivity of the bedrock aquifers. Where the alluvial aquifer consists of the Verdos Alluvium or the Rocky Flats Alluvium, clay and silt content is high, saturated thickness is small, and transmissivity is correspondingly low. Results of aquifer tests in the Rocky Flats Alluvium and other unconsolidated alluvial deposits are presented later in this report.

The effective porosity of an aquifer is related to the porosity of interconnected pores and is a key aquifer characteristic in describing rates of mass transport. Laboratory estimates of porosity for the aquifers of the Denver groundwater basin show a range of 12 to 46 percent with an average of 31 percent. Differences among the bedrock aquifers are minimal. However, total porosity obtained by laboratory analysis is not a reliable measure of effective porosity in lenticular sediments such as the bedrock aquifers of the Denver groundwater basin. In these cases, aquifer tests with tracers are used to estimate effective porosity.

The storage coefficient and specific yield of an aquifer have important effects on water-level changes and on estimates of the amount of water in storage. The storage coefficient expresses the volumetric change in water content per unit change in head. The specific yield of an unconfined aquifer is the ratio of the volume of water that drains from a saturated formation due to gravity forces to the total volume of the formation. The storage coefficients of bedrock aquifers in the Denver groundwater basin are estimated to range from less than 2.0E-04 to more than 8.0E-04 (Robson, 1987). These estimates are applicable to parts of the bedrock aquifers where confining conditions occur. Where unconfined conditions occur, the storage coefficient is equivalent to the specific yield and ranges from 0.01 to 0.38 based on laboratory analysis of samples (McConaghy *et al.*, 1964). Average values for the bedrock aquifers are 14 percent for the Denver aquifer, 18 percent for the Arapahoe and Dawson aquifers, and 20 percent for the Laramie/Fox Hills aquifer. Robson (1989) indicates that the specific yield of the regional alluvial aquifer is about 20 percent.

4.1.3 Groundwater Movement

The large difference in hydrogeologic characteristics of bedrock and alluvial aquifers of the Denver groundwater basin has resulted in substantially different patterns of groundwater movement. Water levels in the bedrock aquifers typically are more than 100 feet below land surface, and groundwater flow is relatively unaffected by surface conditions. Interaquifer leakage and groundwater development by pumping affect flow in bedrock aquifers. In contrast, water levels in the alluvial aquifer generally are near land surface or within a few tens of feet below land surface, and groundwater is affected by percolation of surface water and by the altitude of nearby streams.

Water in the bedrock aquifers moves in the general direction of surface topography. Movement occurs along both local flowpaths and regional flowpaths. Local flowpaths predominate in an aquifer where it is at the land surface and water-table conditions occur. Regional flowpaths predominate in areas where the aquifer is confined by shale layers of an overlying aquifer.

Water in the alluvial aquifer moves in the general direction of surface-water flow. Recharge occurs by percolation downward from irrigated fields, lakes, and water diversion ditches and through soil following rainfall or snowmelt. In general, these conditions occur throughout the areal extent of the alluvial aquifer. Discharge occurs by leakage to streams, phreatophyte evapotranspiration, and seeps. In areas where the alluvial aquifer is well connected to a stream, changes in the stream level will affect the water table, causing either recharge if stream level rises or discharge if stream level is low. Pumpage from the alluvial aquifer also affects groundwater levels and stream levels. Because the transmissivity of the alluvial aquifer is much larger than the transmissivity of bedrock aquifers, the effect of alluvial aquifer pumpage is seasonal in nature. In areas where the alluvial aquifer consists of topographically isolated terrace deposits, discharge occurs by seeps and evapotranspiration near contacts with underlying bedrock aquifers.

Regional water budgets have been prepared for the bedrock aquifers (Robson, 1987) and the alluvial aquifer in the reach of the South Platte River from Denver to Julesburg, in the northeast corner of Colorado (Hurr, 1975). The water budget for the bedrock aquifers (Table 4-1) indicates that recharge equaling 40,200 acre-feet/year occurs as precipitation, with more than 60 percent occurring to the Dawson aquifer. Groundwater discharge to streams is slightly larger than discharge to wells. The water budget for the alluvial aquifer (Hurr, 1975) indicates that total recharge is approximately 914,000 acre-feet/year. Groundwater seepage to streams and pumpage are the two largest components of discharge from the alluvial aquifer. A water budget for the subregional flow system north and west of the South Platte River is presented in Section 4.6 of this report.

Recharge to bedrock aquifers occurs by water percolating from the surface in areas where the aquifer is under water-table conditions. The potentiometric surface in these areas is very irregular and reflects water entering the aquifer from highland areas between stream valleys and leaving the aquifer by moving locally toward streams or the alluvial aquifer. In areas where the water table is higher than the potentiometric surface of the underlying aquifer, water also will tend to move downward and recharge the underlying aquifer.

At greater depth, groundwater is less affected by surface recharge and overlying shale layers tend to produce confined conditions. The potentiometric surface in a deep zone tends to be relatively uniform in shape and slopes gently toward discharge areas. Vertical movement between aquifers occurs in response to head differences but the shale layers tend to restrict vertical movement in preference to horizontal movement along permeable strata. Prior to development, discharge probably occurred to the alluvial aquifer along major streams. However, groundwater pumpage in the Arapahoe and Laramie/Fox Hills aquifers has significantly altered regional points of discharge for bedrock aquifers.

Based on regional configurations of potentiometric surfaces of bedrock aquifers and an understanding of recharge and discharge areas, it is possible to divide the Denver groundwater basin into three subregions. Groundwater movement in one of these subregions is essentially independent of hydrogeologic conditions in other subregions.

North and west of the South Platte River groundwater in bedrock moves from recharge areas along the margin of the basin toward discharge areas beneath the South Platte River. Prior to development, discharge probably occurred to the alluvial aquifer along the South Platte River. However, water-level declines on the order of several hundred feet have occurred in the past 100 years as a result of water development, and the potentiometric surface in the bedrock aquifers currently is below stream level. Discharge from bedrock aquifers presently occurs to wells. Rocky Flats is located in this subregion.

The largest subregion of the Denver groundwater basin is located east and south of the South Platte River. This subregion is bounded on the east by the lateral extent of the aquifer system and on the south by the surface drainage divide located roughly along the northern boundary of El Paso County, 20 miles north of Colorado Springs. Groundwater in this subregion moves in a northerly direction from recharge areas along the surface drainage divide to discharge areas along the South Platte River. Deeper aquifers are recharged by vertical leakage from overlying aquifers in the southern part of this subregion. Groundwater in the surficial aquifer discharges locally to alluvium along streams. Regionally, discharge occurs to the alluvium along the South Platte River south of Greeley and to large production wells in the bedrock aquifers.

The third subregion of the Denver groundwater basin is located south of the surface drainage divide along the northern boundary of El Paso County. Groundwater in this

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subregion moves in a southerly direction from recharge areas along the surface drainage divide to discharge areas along Monument Creek and other streams. In these stream valleys, water from the bedrock discharges into the streams or the alluvial aquifers along the streams, or it is transpired by vegetation growing in the valleys.

4.1.4 Groundwater Development and Use

Both bedrock and alluvial aquifers have been developed extensively for water supply. In general, pumpage in the bedrock aquifers has had a large impact on water levels. Pumpage in the alluvial aquifer has had only seasonal impacts.

The first deep wells were drilled in the Denver area in 1884, and it was discovered that wells would flow without being pumped. This discovery lead to rapid development of the resource. The resulting declines in water levels caused wells to stop flowing. By 1960, declines of 400 to 500 feet had been observed near Denver. Since 1960, pumping near downtown Denver has declined, while pumping in suburban areas has continued to increase. As a result, water-level declines exceeding 200 feet have occurred in the Laramie/Fox Hills aquifer over an 80-square-mile area near Brighton and in the Arapahoe aquifer over a 135-square-mile area near Cherry Creek Lake.

Groundwater in the alluvial aquifer is used extensively for irrigation and to a lesser degree for municipal, domestic, and industrial needs. However, in valleys with perennial streams, such as the South Platte River, water-level declines have occurred primarily during the growing season. In these valleys, water levels tend to recover rapidly during the winter months when wells are not used. Pumping has produced water-level declines greater than 30 feet in the alluvial aquifer east of Denver where streams are not perennial. Groundwater in isolated portions of the alluvial aquifer formed by the Verdos Alluvium and the Rocky Flats Alluvium have undergone little development for water supply. The lack of development probably is a result of the limited ability of these sediments to yield water.

Records of the Office of the Colorado State Engineer indicate that 239 wells are permitted within a 5-mile radius of Rocky Flats (Table 4-2). The majority of these wells are located more than 3 miles from Rocky Flats with the greatest density of permitted wells in T1S, R69W, Sec. 19 and Sec. 29. In general, more wells are located east and south of Rocky Flats than other directions. However, a significant number of wells are located northeast of Rocky Flats near Superior. Locations of wells in Table 4-2 have not been field checked.

The compilation in Table 4-2 retains English units of measure used by the Office of the Colorado State Engineer and includes all permitted wells without regard to the completeness of the yield and depth data. Previously published compilations of well permits near Rocky Flats considered only wells with a recorded yield or depth;

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however, well yield and depth are not recorded for approximately 40 percent of the permitted wells. Sixteen of the wells are permitted for municipal use, and 18 are permitted for industrial or commercial use. Two wells are permitted for irrigation use, and the balance are permitted for domestic and related use. Of the 150 wells where a yield is reported, 3 wells yield 30 to 100 gallons per minute (gpm), and 6 wells yield greater than 100 gpm. The maximum reported yield is 600 gpm. The remaining wells reported a yield of less than 30 gpm.

Well depth is reported for 156 wells. Records for 36 wells indicate a depth greater than 400 feet. The maximum reported depth is 1,300 feet. Records for 40 wells indicate a depth less than 100 feet. The records for the remaining 80 wells indicate a depth between 100 and 400 feet. No relationships between well depth and location are readily apparent. Wells with reported yields greater than 100 gpm consistently are constructed to depths greater than 400 feet. However, many deep wells also have low yields.

4.1.5 Groundwater Quality

The quality of water in the Denver groundwater basin is a reflection of the quality of recharge water and the residence time of the groundwater within geologic materials. Differences in hydrogeologic characteristics and flow patterns of the bedrock and alluvial aquifers have resulted in distinctly different water quality.

The total dissolved solids (TDS) concentration of water in the bedrock aquifers generally is less than 200 mg/L in the Dawson aquifer where groundwater is recharged directly from precipitation. At greater depths, such as the central part of the basin, water quality has been degraded through prolonged contact with geologic materials. In the center of the basin, TDS values typically range from 400 to 600 mg/L. The dissolved-solids concentration in the Laramie/Fox Hills and Arapahoe aquifers is high along the margin of the basin; a range of 600 to 1200 mg/L is typical. Dissolved sulfate in the Laramie/Fox Hills aquifer may range from 25 to more than 250 mg/L. Robson (1989) suggests that the increase may be a result of the predominance of local flowpaths. Along the basin margins, water may discharge from the bedrock aquifers to streams or to the alluvial aquifer or may be lost by evapotranspiration. Evapotranspiration, coupled with leaching of soluble minerals from the soil into the aquifer, produces local increases in TDS in these areas.

Water-quality data obtained from deep wells completed in the Laramie/Fox Hills aquifer near Rocky Flats and at the U.S. Department of Energy Wind Research Site show dissolved-solids concentrations that ranged from 200 to 714 mg/L. With one exception, sulfate concentrations were less than 10 mg/L. These data were obtained in

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1976 and showed an increase in concentration from west to east. The results are consistent with regional water-quality maps of Robson (1989).

Water in the alluvial aquifer is derived primarily from local recharge by surface water in streams, irrigation ditches, and irrigated fields. As a result, the water quality in the alluvial aquifer is a close reflection of the water quality of the surface water. In upstream reaches, surface water is of very good quality and adjacent alluvial groundwater typically has TDS values less than 300 mg/L. As surface water flows downstream, inflows from municipal sewage treatment plants and other sources degrade water quality. Return flow of water used for irrigation is an important contributor to water-quality degradation as evapotranspiration tends to concentrate the dissolved minerals. Leaching of soluble minerals in soil in irrigated areas also results in diminished water quality.

The TDS values of water in the alluvial aquifer along the South Platte River exceed 500 mg/L, with areas greater than 1,000 mg/L downstream of Denver, and consistently exceed 1,000 mg/L downstream of Greeley. In addition to an increase in concentrations of dissolved calcium, sodium, iron, magnesium, bicarbonate, sulfate, and nitrate, concentrations of agricultural chemicals increase in the downstream direction.

4.2 Alluvial Aquifer in the Northwest Subregion

The alluvial aquifer in the northwest subregion occurs in present stream valleys and ancestral stream valleys and on terraces. Alluvial aquifers that are in or adjacent to present and ancestral stream valleys are generally continuous, hydraulically connected, and perennially saturated. This groundwater system is referred to as the regional alluvial aquifer (Figure 4-2). Older alluvial deposits that occur at higher elevations, may or may not be perennially saturated. These older deposits are generally discontinuous and topographically elevated from present-day stream valleys and occur as isolated remnants on pediments. The older alluvial deposits do not form a single hydrostratigraphic unit in the subregion. The hydrogeologic connection of the terrace and valley-fill deposits depends on local features such as topography, bedrock paleotopography, and permeability. These features at Rocky Flats are evaluated in Section 6 of this report. The importance of unconsolidated deposits on the subregional scale is primarily as an area of recharge.

Information on the regional alluvial aquifer is derived primarily from a series of reports prepared by the USGS on the geology, hydrogeology, and geochemistry of the Front Range urban corridor and geologic maps prepared by Colton (1978) and Trimble and Machette (1979). Data on the depth to the water table, water yields, and chemical water quality are presented in Hillier and Schneider (1979a and 1979b) and Hillier *et*

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al. (1983a and 1983b). Additional information on the groundwater quality of the regional alluvial aquifer was obtained from Robson (1989). The USGS is currently preparing a comprehensive report of the alluvial aquifer in the Denver metropolitan area (Robson, 1994).

4.2.1 Regional Valley-Fill Deposits

The Post-Piney Creek Alluvium and Piney Creek Alluvium are present along the course of the South Platte River and its tributaries, including Clear Creek, Van Bibber Creek, Ralston Creek, Little Dry Creek, Big Dry Creek, Rock Creek, Coal Creek, Boulder Creek, and South Boulder Creek. The grain size of these valley-fill deposits decreases in the downstream direction. Depth to water in the valley-fill aquifer is less than 5 feet beneath stream channels and between 5 and 10 feet beneath adjacent flood plains.

The thickness of the alluvial aquifer within the subregion ranges from less than 20 feet at the upstream reaches of the streams to 80 feet near Platteville (15 miles north of Fort Lupton). Hydraulic conductivity values for the valley-fill aquifer generally range from 100 to over 1,000 feet per day. Along the South Platte River, hydraulic conductivity decreases in the downstream direction and with decreasing grain size. Transmissivity estimates for the valley-fill aquifer generally increase with increasing thickness of the alluvial deposits and are in excess of 20,000 square feet per day in the vicinity of Platteville. Well yields increase with increasing thickness of deposits and exceed 1,500 gpm in the Brighton reach of the South Platte River. Declines in the water-table due to pumping ranged from 0 to 20 feet between 1969 and 1979. Decreases in water levels generally are smaller in valleys with perennial streams. The TDS values are less than 500 mg/L in the upper reaches of the aquifer and increase to 2,000 mg/L in developed and irrigated areas, located further downstream.

Recharge of the valley-fill deposits occurs by infiltration of stream water, discharge from underlying bedrock aquifers, and drainage from hydraulically connected surficial deposits. Percolation of surface water used for irrigation or diverted to irrigation canals and lakes also provides significant recharge to the alluvial aquifer. The percentage of surface water that returns to the alluvial aquifer depends on a number of factors, including the condition of irrigation canals (lined versus unlined), permeability of soil, and rates of evapotranspiration. The amount of surface water that recharges the alluvial aquifer by percolation of applied water and seepage from the irrigation system for two drainage basins in Westminster was estimated to be 21 and 22 percent (Tipton & Kalmbach, Inc., 1989). Robson (1989) estimates that 45 to 50 percent of water used for irrigation returns to the valley-fill aquifer by percolation in areas of extensive irrigation. Discharge of groundwater in the valley-fill aquifer is by infiltration into bedrock aquifers, evapotranspiration, and pumping.

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4.2.2 Regional Alluvial Terrace Deposits

Alluvial terrace deposits in the subregion are, in order of increasing age, the Broadway Alluvium, Louviers Alluvium, Slocum Alluvium, and the Verdos Alluvium. The elevation of these deposits above present-day stream levels increases with increasing age. The Broadway Alluvium and Louviers Alluvium are perennially saturated throughout most of the subregion. The Broadway Alluvium is more common in the eastern portion of the subregion, where depth to water ranges from 5 to greater than 20 feet. Depth to water in the western portion of the subregion is deeper, ranging from 10 to greater than 20 feet. Terraces of the Louviers Alluvium are more common in the eastern portion of the subregion where the depth to water is generally greater than 20 feet. Well yields in the Broadway and Louviers Alluvium are less than 500 gpm. Discharge of groundwater from the Broadway Alluvium and Louviers Alluvium occurs at seeps, by evapotranspiration, into valley-fill deposits or underlying bedrock aquifers. The TDS values are similar to those in adjacent Piney and Post-Piney Creek Alluvium and are highest in developed and irrigated areas.

The Slocum Alluvium and Verdos Alluvium are older terrace deposits that are located as much as 250 feet above the level of modern streams (EG&G, 1992c). Depth to groundwater in these deposits appears to depend on topographic relief and proximity to streams. Groundwater occurs at depths greater than 20 feet in topographically high areas. Where the deposits are closer to stream valleys, groundwater is shallower, occurring at depths less than 5 feet. These deposits are generally small and isolated and in many locations are not perennially saturated. The deposits are drained by downward vertical movement of groundwater into the underlying bedrock aquifers and lateral movement along the top of bedrock surfaces to groundwater seeps.

The Rocky Flats Alluvium is an alluvial-fan deposit located primarily within a 36-square-mile area near the mouth of Coal Creek Canyon. The Rocky Flats Alluvium has been eroded extensively by streams and has a present-day areal extent of approximately 16 square miles. The deposit is elevated topographically as much as 380 feet above the level of modern streams (EG&G, 1992), and depth to groundwater is between 10 and 20 feet. Alluvial fans of similar size and extent are not present elsewhere in the subregion.

Large remnants of Rocky Flats Alluvium, Verdos Alluvium, and Slocum Alluvium are present in the western portions of the subregion, such as the Rocky Flats Alluvium near Rocky Flats and the Slocum Alluvium and Verdos Alluvium in the vicinity of Boulder. Parts of these larger deposits remain saturated throughout the year and maintain well yields that are less than 500 gpm. The TDS values of perennially saturated portions of the Rocky Flats Alluvium are generally less than 500 mg/L. Dissolved-solids

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concentrations of the Slocum Alluvium and Verdos Alluvium are more variable, with concentrations above and below 500 mg/L in the western portion of the subregion.

4.3 Denver Aquifer in the Northwest Subregion

The Denver aquifer occurs in the southern portion of the subregion and is not present at Rocky Flats (Figure 4-2). Rocky Flats is located approximately 5 miles northwest of the northern Denver aquifer. Information provided in this section of the report was obtained from Robson (1983 and 1989) and Norris *et al.* (1985). Additional sources are referenced in the text.

The base of the Denver aquifer occurs at elevations ranging from 4,950 to 5,600 feet and dips to the southeast. The aquifer consists of interbedded shale, claystone, siltstone, and sandstone in which coal and fossilized plant remains are common. Thickness of the sandstone and siltstone water-bearing strata within the subregion ranges from 0 to approximately 120 feet and increases parallel to the aquifer margin. Unconfined and partially saturated conditions commonly occur within the subregion, and depth to groundwater is commonly greater than 100 feet below ground surface. In the eastern portion of the subregion where the Denver aquifer is overlain by colluvial deposits and in stream valleys, depth to groundwater may be less than 5 feet. Groundwater elevations in 1993 ranged from 5,100 to 5,600 feet. Groundwater flows from the western margin of the aquifer to the east, into a groundwater trough. The trough originates south of Littleton and follows the South Platte River northeast to the aquifer margin. Horizontal hydraulic gradients, calculated from a 1993 potentiometric-surface map (Romero and Bainbridge, 1993), ranged from 0.008 to 0.03 and were steepest near the western margin of the aquifer. Between 1958 and 1978, groundwater elevations in the southern portion of the subregion increased.

The average hydraulic conductivity within the subregion is 0.5 feet per day (1.8E-04 cm/sec). Transmissivity estimates within the subregion are low, less than 50 ft^2/day, as compared with 300 to 400 ft^2/day in areas where the aquifer is confined (south of the subregion boundary).

Recharge within the subregion occurs by infiltration of precipitation and irrigation water. Water percolates directly to the aquifer where it outcrops or through colluvial, wind-blown, and terrace deposits that overlie the aquifer. Groundwater from the alluvial aquifer may also provide recharge to the Denver aquifer. The alluvial aquifer may also be a discharge point for groundwater. The recharge/discharge relationship of the alluvial aquifer and the Denver aquifer may vary with changing water elevations in each aquifer.

Dissolved-solids concentrations in the Denver aquifer range from 300 to 1,000 mg/L within the subregion. The concentrations increase to the northeast, in the downgradient

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direction. Sulfate concentration is greater than 250 mg/L throughout the subregion. The groundwater is characterized as sodium-sulfate type water.

4.4 Arapahoe Aquifer

The Arapahoe aquifer subregion extends from the vicinity of Eldorado Springs, northeast toward Frederick (Figure 4-2). The aquifer generally outcrops or subcrops beneath unconsolidated alluvial, wind-blown, and colluvial deposits. The base of the aquifer occurs at elevations ranging from 4,200 to 5,500 feet and dips to the east and southeast. The highest elevations and steepest dips occur along the western margin of the aquifer. Information on the Arapahoe aquifer is primarily derived from USGS reports prepared by Robson (1983 and 1987) and Robson *et al.* (1981a). Other sources are cited in the text.

The Arapahoe aquifer consists of interbedded conglomerate, sandstone, siltstone, and shale. Individual sandstone and conglomerate beds generally are lenticular and limited in areal extent. Total thickness of the water-bearing strata ranges from less than 50 to approximately 200 feet in the subregion and is thinnest along the western margin of the aquifer. The thickness generally increases parallel to the aquifer margin. Throughout most of the subregion, the Arapahoe aquifer is partially saturated and overlain with unconsolidated deposits.

The potentiometric surface in the Arapahoe aquifer is highest along the western margins of the aquifer (Figure 4-3). Groundwater elevations in the subregion range from 5,000 to 6,100 feet. A 1978 potentiometric-surface map (Robson *et al.*, 1981a) can be used to infer groundwater flow from the basin margins east and southeast into a groundwater trough that extends along the South Platte River to the area northeast of Brighton. In this trough, groundwater from the subregion converges with groundwater from southern and eastern parts of the Denver basin. The trough probably originated as a result of groundwater discharge from the Arapahoe aquifer into overlying alluvial deposits along the South Platte River. Because of extensive pumping in the area, the trough has deepened and grown over the past 100 years and discharge from the Arapahoe aquifer occurs primarily at well heads. Horizontal hydraulic gradients in the Arapahoe aquifer range from 0.009 to 0.03 and are steepest in the vicinity of Rocky Flats. In general, the magnitude of the horizontal hydraulic gradient in the subregion decreases to the east.

Comparison of potentiometric-surface maps from 1958, 1978, and 1993 (Robson *et al.*, 1981a; Romero and Bainbridge, 1993) illustrates some of the temporal changes pumping has had on the direction of groundwater flow. The 1958 potentiometric-surface map showed groundwater flowing south from the vicinity of Northglenn into a groundwater low centered near Commerce City. North of Northglenn, groundwater

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flow is to the north-northeast, toward the groundwater trough. Groundwater in the southwestern portion of the subregion flowed southeast, toward a depression centered at Denver.

In the 1978 potentiometric-surface map, a groundwater divide in the vicinity of Northglenn was absent and groundwater flow directions were to the north-northeast, toward the groundwater trough. In 1978, groundwater from the southwestern portion of the subregion flowed southeast but then continued northeast toward the groundwater trough. The depression near Commerce City was smaller and shallower than in 1958.

The 1993 potentiometric-surface map showed that a divide in the vicinity of Northglenn was re-established. Groundwater flow was toward the southeast, into a groundwater depression near Commerce City, and to the north-northeast, into the groundwater trough.

Hydraulic conductivity values calculated for the subregion range from 0.5 to 3.7 feet per day (1.8E-04 to 1.2E-03 cm/sec). These estimates are based on results from pumping tests and laboratory testing of undisturbed sediment samples. The highest values were in the vicinity of Northglenn. An average hydraulic conductivity of 2 feet per day occurs in an area that encompasses Standley Lake, Broomfield, Brighton, and Northglenn. Elsewhere in the subregion, the average hydraulic conductivity is 0.5 feet per day. Transmissivity estimates in the subregion range from 0 to less than 300 ft^2/day. The lowest values are located along the western margin of the aquifer and increase eastward with increasing aquifer thickness. Estimates of storage coefficients within the subregion ranged from 2E-04 to 4E-04. However, because the aquifer is unconfined or partially saturated within most of the subregion, these values are not indicative of conditions in the aquifer. Specific yield values are generally orders of magnitude larger than storage coefficients.

Within the subregion, groundwater recharge to the Arapahoe aquifer is limited to areas where the aquifer outcrops or subcrops beneath unconsolidated wind-blown, colluvial, and alluvial deposits. Recharge may occur by infiltration of water from the overlying deposits. The alluvial aquifer, which was a major discharge point prior to water-level declines of several hundred feet due to pumping, may be a discharge point along small reaches of associated stream valleys. Recharge/discharge relationships between the Arapahoe and alluvial aquifers are controlled by local conditions. Discharge from the Arapahoe aquifer also occurs in stream valleys where the aquifer is at or near the ground surface. Between 1880 and the present, groundwater elevations in the Arapahoe aquifer (measured in downtown Denver) decreased by as much as 350 feet. Between 1988 and 1993, groundwater elevations within most of the subregion decreased less than 50 feet. The largest decline in water levels during this period was

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in the vicinity of Northglenn, where decreases in the potentiometric surface ranged from 50 to 100 feet.

Dissolved-solids concentrations in the subregion range from approximately 200 to 2,000 mg/L, and water is classified as sodium-bicarbonate or calcium-bicarbonate type. In general, concentrations are highest near the aquifer margin and decrease with increasing distance from the margin and increasing thickness of the aquifer. Exceptions are downgradient of Standley Lake, where concentrations are over 1,400 mg/L, as compared to less than 600 mg/L in adjacent areas. Dissolved-solids concentrations between Welby and Commerce City are approximately 200 mg/L higher than in surrounding areas. Concentrations are higher near the margins of the aquifer due to infiltration of poorer quality surface water. As the thickness of the aquifer increases, there is more dilution of the infiltrating surface water with higher quality groundwater, and dissolved-solids concentrations are lower.

Dissolved-sulfate concentrations and hardness values are also higher along the margins of the Arapahoe aquifer. Dissolved-sulfate concentrations in excess of 1,000 mg/L occur along the western and northern limits of the aquifer, as compared to less than 25 mg/L in the vicinity of Welby. Similarly, very hard groundwater (i.e., greater than 180 mg/L of hardness as calcium carbonate) is limited to within approximately 5 miles of the margins of the Arapahoe aquifer. Hard groundwater (hardness ranging from 60 to 180 mg/L as calcium carbonate) is present east of the very hard groundwater. This zone of the hard groundwater runs the entire length of the subregion and ranges in width from 1 mile to approximately 7 miles. Groundwater in the remainder of the subregion is soft, with a hardness less than 60 mg/L as calcium carbonate. The hardness of the water may be related to the distribution of alluvial deposits. The Rocky Flats, Verdos, and Slocum Alluvium each occur along the western margin of the Arapahoe aquifer. These deposits all contain significant amounts of calcium carbonate in upper portions of the deposits. Infiltration of surface water through the alluvium into the Arapahoe aquifer would result in groundwater with increased hardness. The occurrence of these alluvial deposits decreases with increasing distance from the aquifer margin, and the hardness of groundwater is lower.

4.5 Upper Laramie Confining Unit

The upper part of the Laramie Formation forms a confining unit between the Arapahoe aquifer and the underlying Laramie/Fox Hills aquifer. The upper Laramie confining unit is composed of gray to black claystone, coal seams, and minor amounts of gray siltstone and sandstone. The subbituminous to lignitic coal seams ranging in thickness from a few inches to hundreds of feet have been mined extensively. At Rocky Flats, the unit is estimated to be as much as 800 to 900 feet thick. At the Boulder-Marshall Landfill the unit is 450 to 630 feet thick (Fox Consultants, 1984).

Because the upper Laramie Formation functions hydraulically as a confining unit, the primary characteristic of importance is the vertical hydraulic conductivity. Estimates of this characteristic are not available from well tests. However, Robson (1987) evaluated the vertical hydraulic conductivity during calibration of a regional flow model. He determined that comparisons between measured and simulated hydraulic head in the Arapahoe and Laramie/Fox Hills aquifers were acceptable only if vertical hydraulic conductivity of the upper Laramie confining unit was less than 8.0E-07 feet per day (2.8E-10 cm/sec).

4.6 Laramie/Fox Hills Aquifer

The Laramie/Fox Hills aquifer is present throughout much of the subregion and outcrops or subcrops in the north and northwestern portions (Figure 4-2). Robson (1983 and 1987), Robson and Banta (1987), and Robson *et al.* (1981b) are the primary sources for information presented in this section of the report. Additional information was obtained as referenced in the text.

The Laramie/Fox Hills aquifer is composed of the upper sandstone and siltstone units of the Fox Hills Sandstone and the basal sandstone units of the Laramie Formation. The basal sandstone units of the Laramie Formation have been designated the A and B sands. The A sand is composed of sandstone and is located 5 to 40 feet above the base of the formation. The B sand varies from a single massive sandstone to a series of thin sandstone beds with claystone interbeds and is located approximately 20 feet above the top of the A sand. The upper portion of the Laramie Formation, which consists of gray to black claystone, coal seams, and thin beds of siltstone and sandstone, forms a confining unit. The base of the aquifer occurs at elevations ranging from 3,700 to 5,100 feet above sea level and dips steeply toward the southeast. The structure contours of the top of the Laramie Formation are similar to the aquifer base and range from 4,000 to 5,400 feet in elevation.

The total thickness of the water-bearing strata in the subregion ranges from 0 to greater than 200 feet and is thinnest along the western margin of the aquifer. Thickness increases roughly parallel to the aquifer margin. The aquifer is greater than 200 feet thick slightly northeast of Northglenn and south of Frederick. In the vicinity of Superior, the percent sandstone is greater than in surrounding areas, and thickness is greater, ranging up to 360 feet (Schneider, 1980).

There is extensive faulting in the west-central portion of the subregion. The northeast-trending fault zone extends from approximately 1 mile north of the Jefferson-Boulder county line (near the intersection of Colorado Highways 93 and 128) northeast, approximately 30 miles, to Frederick in Weld County. The fault zone is approximately 10 miles wide (Colton and Lowrie, 1973). In Boulder County, the faults trend

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predominantly to the northeast. North-northeast-trending faults are more common in the northern portions of Boulder County and in Weld County. Faults south of the Boulder-Jefferson county line, where the Laramie/Fox Hills aquifer subcrops, have been suggested by borehole geophysical logs. The northeast trend of Coal Creek and Rock Creek in Jefferson county also suggests the continuation of faults into this area. A comprehensive discussion of faulting in the vicinity of Rocky Flats, including geologic cross sections and maps, is presented in the Geologic Characterization Report (EG&G, 1995a).

Faulting in the Laramie/Fox Hills aquifer creates complex groundwater flow patterns, where abrupt changes in groundwater elevations occur across fault zones. An example of the hydrologic effect of faulting is provided in the site characterization of the Boulder-Marshall Landfill (T1S, R70W, Sec. 22 and Sec. 23) conducted as part of a remedial investigation. Faulting near the Boulder-Marshall Landfill has placed claystones of the upper Laramie Formation against sandstones of the Laramie/Fox Hills aquifer and significantly restricted lateral flow (Fox Consultants, 1984).

Hydraulic conductivity values calculated from pump tests, specific capacity tests, and laboratory analyses of sedimentary rocks for the subregion ranged from 0.003 to 1 foot per day. The aquifer tests included fully and partially penetrating wells, in addition to wells that were screened across more than one aquifer. Therefore, the data from these wells provide reasonable estimates of aquifer parameters, rather than exact measurements. Robson (1983) used the results to derive average hydraulic conductivity estimates for larger portions of the Laramie/Fox Hills aquifer. The average hydraulic conductivity estimate in the western half of the subregion was 0.05 feet per day. Exceptions were in Boulder County, from Marshall north approximately 8 miles, and north of Lake Thomas (16 miles north of Frederick), where the average hydraulic conductivity was estimated to be 0.5 feet per day. The average hydraulic conductivity in the eastern and northernmost portions of the subregion also was estimated to be 0.5 feet per day. Transmissivity estimates in the subregion range from 0 to greater than 70 ft^2/day. The lowest values were obtained from areas near the western margin of the aquifer and show a positive correlation with aquifer thickness. Transmissivity estimates in excess of 70 ft^2/day were calculated for the eastern portion of the subregion, between Welby and Brighton, and in the northeast corner of the subregion. Estimates of storage coefficients within the subregion ranged from 2E-04 to 4E-04. However, these values are only realistic for portions of the aquifer that are confined.

The potentiometric surface in the Laramie/Fox Hills aquifer is highest near the southwestern margin of the aquifer and lowest in the northeast portion of the subregion (Figure 4-4). Groundwater elevations in the subregion are lower than those in the Laramie/Fox Hills aquifer elsewhere in the Denver Basin. In the central portion of the

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subregion, there is a major groundwater trough that originates near Littleton and extends northeast toward Brighton, resulting from groundwater discharge to the alluvial aquifer along the South Platte River and tributaries. As a result, groundwater from the south and southeast portions and west-central margins of the Denver Basin converge within the subregion. Groundwater flows northeast from the trough toward Fort Lupton. The trough has been deepened and expanded by increased pumping by the surrounding communities. However, comparison of potentiometric-surface maps from 1958 (Robson *et al.*, 1981b) and 1978 (Romero and Bainbridge, 1993) show that the direction of groundwater flow over the 20-year period has been similar.

Groundwater flow within the subregion is further complicated by northeast-trending faults located slightly northwest of the axis of the groundwater trough. Groundwater elevations change abruptly across the fault zones. However, the influence of the faulting in the Laramie/Fox Hills aquifer on groundwater flow is not well understood. Schneider (1980), in a detailed investigation of the southern half of the subregion, shows that groundwater flow, although generally toward the northeast, is locally complex with depressions in the potentiometric surface that result from pumping and mounds that result from recharge. Schneider suggested several hypotheses for a groundwater mound east of Lafayette. The mound may result not from recharge but from the northeast-trending faults in the area. These faults may act as barriers to flow, and therefore drawdowns due to pumping are minimized near the faults. Alternatively, the fault planes may provide a preferential flowpath for groundwater movement from the overlying alluvial deposits. Schneider also recognized that the groundwater mound near Lafayette may be a result of leakage from improperly designed or corroded wells.

Horizontal groundwater hydraulic gradients in the Laramie/Fox Hills aquifer range from 0.002 to 0.08. These values were calculated using a 1983 potentiometric-surface map prepared by Robson and Banta (1987). Potentiometric maps prepared annually by the Office of the State Engineer (Romero and Bainbridge, 1993) provide data only for the area east of the northeast-trending fault zone. Where 1993 data were available, horizontal hydraulic gradients were similar to those calculated with the 1983 data, ranging from 0.008 to 0.03. The shallowest gradients were near the northwestern margin of the Laramie/Fox Hills aquifer, north of Fort Lupton and Frederick. The aquifer in this area is partially saturated and subcrops beneath unconsolidated deposits. Groundwater flow in this area is to the northeast. The steepest gradients occur at Rocky Flats. The regional direction of horizontal hydraulic gradient at Rocky Flats is east-southeast. Steep gradients in the vicinity of Rocky Flats may result from enhanced recharge in areas where the Rocky Flats Alluvium is consistently saturated and the edge of the subcropping Laramie/Fox Hills aquifer is upturned. Gradients are also steep slightly north of Rocky Flats at Lake and Davidson mesas, where the aquifer is recharged by leakage from irrigation canals and reservoirs in the overlying unconsolidated deposits. In addition, the northeast-trending faults that intersect the

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mesas may also affect groundwater flow and horizontal hydraulic gradients.

Comparison of potentiometric surfaces on the subregional and local scale illustrates the influence that local conditions have on the movement of shallow groundwater. Groundwater monitoring at Rocky Flats has shown that groundwater flow in the bedrock aquifers at Rocky Flats is more complex than shown on the subregional scale, with horizontal hydraulic gradients oriented toward the east, southeast, and northeast (EG&G, 1994a). Local flow patterns are controlled by topography, spatial variations in aquifer properties, and discharge/recharge relationships with surface water bodies and the overlying unconsolidated deposits. These features are described in greater detail in Section 6 of this report.

Recharge to the Laramie/Fox Hills aquifer takes place along the western margin of the Laramie/Fox Hills aquifer where the upturned portions of the aquifer crop out. Recharge also occurs by the infiltration of precipitation through the unconsolidated wind-blown and alluvial deposits in areas where the aquifer subcrops. Leakage of water from canals and reservoirs into the unconsolidated deposits also provides significant recharge to the bedrock aquifer. In addition, the northeast-trending faults may also provide a preferential pathway for groundwater recharge. Historically, the regional discharge point for groundwater from the Laramie/Fox Hills aquifer was to tributaries downgradient of the recharge area where the aquifer subcrops beneath alluvial aquifers or crops out. Because of extensive pumping of the Laramie/Fox Hills aquifer, potentiometric heads are now lower than in the alluvial aquifers and the primary discharge points are at well heads. The greatest declines in water levels due to pumping have been in the vicinity of Northglenn and Brighton. Between 1958 and 1983, the potentiometric surface declined by over 300 feet in this area. Water-level declines at Rocky Flats for this period have been negligible.

Dissolved-solids concentrations in the subregion range from less than 200 to more than 2,000 mg/L, and water is classified as sodium-bicarbonate type. In general, the highest TDS values are found where water-table conditions exist. Robson *et al.* (1981b) suggest that the more mineralized groundwater in these areas may result from the movement of solutes derived from soluble minerals in surface sources and in the upper clayey portion of the Laramie Formation into the aquifer. Concentrations of TDS increase in a downgradient direction from approximately 300 mg/L at Rocky Flats to 1,200 mg/L near Frederick. Isolated areas with TDS concentrations in excess of 2,000 mg/L occur slightly north of Louisville. North of Frederick, TDS concentrations increase parallel to the margins of the aquifer, from 600 to 1,200 mg/L near Platteville (15 miles north of Fort Lupton). Dissolved-solids concentrations decrease from over 400 mg/L to less than 200 mg/L in the downgradient direction between Golden and Rocky Flats.

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The distribution of dissolved-sulfate and hardness in the Laramie/Fox Hills aquifer is similar to that of dissolved solids. The highest values occur near the margins of the aquifer, in areas where the aquifer is overlain with unconsolidated deposits and is partially saturated. Concentrations of dissolved-sulfate in the subregion range from less than 25 mg/L to greater than 250 mg/L. Groundwater hardness, expressed as calcium carbonate, ranges from less than 60 to more than 180 mg/L.

4.7 Aquifer Interchange and Subregional Water Budget

A water-table map of the alluvial aquifer (Norris *et al.*, 1985) in the Denver Basin was used, in conjunction with the potentiometric-surface maps, to assess the direction of the vertical gradients between the regional valley-fill aquifer and the underlying bedrock aquifers. Downward vertical gradients between the Denver aquifer and the alluvial aquifer were present near the northeast and southeast corners of the subregion. Elsewhere in the subregion, the groundwater elevations in the alluvial aquifer and the underlying bedrock aquifers differed by less than 100 feet. The direction of the vertical gradient could not be determined in these areas because the contour interval for all maps was 100 feet.

On the subregional scale, assessment of the vertical movement of groundwater between the alluvial and bedrock aquifers is simplified. In reality, groundwater movement depends on local features such as topography, paleotopography, and permeability, which are described in detail in Section 6 of this report. In addition, there are temporal changes in the direction of groundwater movement between the alluvial and bedrock aquifers (EG&G, 1994a).

The potentiometric surface in the Denver aquifer is 0 to 300 feet higher than in the underlying Arapahoe aquifer throughout most of the subregion. Therefore the direction of the vertical gradient between the two aquifers is downward. An upward gradient is present in a small area near Commerce City, where the difference in hydraulic head between the two aquifers is less than 100 feet.

The vertical hydraulic gradient between the Arapahoe aquifer and the underlying Laramie/Fox Hills aquifer is in a downward direction throughout most of the subregion and ranges in magnitude from 0 to 0.6. In the vicinity of Rocky Flats, the average vertical gradient between the Arapahoe and Laramie/Fox Hills aquifers is downward and ranges from 0.3 to 0.4. Upward gradients exist only in the vicinity of Golden and Arvada, where the potentiometric surface in the Laramie/Fox Hills aquifer is as much as 200 feet higher than in the overlying aquifer. The vertical hydraulic gradients indicate a potential for groundwater movement. However, the thick (several hundred feet), low-permeability claystone deposits in the upper portion of the Laramie/Fox Hills formation provide a confining layer between the two aquifers, restricting the rate of vertical groundwater movement.

A groundwater budget has been constructed for the portion of the Denver groundwater basin northwest of the South Platte River. The budget was constructed to describe the relative significance of recharge, discharge, and interaquifer flow rates within the subregional flow system. Robson (1987 and 1989) provides a regional water budget for bedrock aquifers of the basin that is based on results of a numerical groundwater flow model. The regional budget was based on the years 1958 to 1978 and reported volumetric flux rates that represented averages for this time period. The subregional water budget presented in the following section also was based on the years 1958 to 1978 and represents average conditions for this time period.

Information contained in Robson (1987) and Robson (1989) was used to construct the subregional water budget. Information in these references for each aquifer includes structure contour maps, transmissivity maps, estimates of vertical hydraulic conductivity, storage coefficient maps, potentiometric-surface maps, and water-level change maps.

The subregional water budget is summarized in Table 4-3. Recharge to the bedrock aquifers was assumed to result from precipitation and seepage through alluvial cover and was estimated from basin-wide values provided by Robson (1989).

Interaquifer leakage was estimated from elevations of the base of each aquifer, the areal distributions of hydraulic head calculated by the regional model for each aquifer, and vertical hydraulic conductivity values used in the calibrated model (Robson, 1987, Figures 5 and 15 and Plate 2). The resulting subregional water budget shows that water movement is downward (on average) from the Denver aquifer to the Arapahoe aquifer. Leakage between the Arapahoe and Laramie/Fox Hills aquifers is negligible.

The decline in storage was obtained from 1958 to 1978 change-in-head maps and storage-coefficient maps for each aquifer (Robson, 1987, Figures 9 and 11). A positive value for decline in storage indicates that water levels generally declined in the subregion. From 1958 to 1978, water levels generally rose in the Denver and Arapahoe aquifers and declined in the Laramie/Fox Hills aquifer.

Discharge to the alluvial aquifer was assumed to be negligible. Hydraulic head in the bedrock aquifers generally is significantly below water levels in streams. Where the heads are similar, such as along Clear Creek, horizontal gradients in the aquifer support the assumption that the alluvium acts to recharge the bedrock aquifer.

Data to estimate well pumpage generally are not available for the period 1958 to 1978. During flow model development, Robson (1987) found that pumpage estimates

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obtained from available data were not sufficient to provide a good model calibration. Robson increased the pumpage estimate to obtain an acceptable match between model calculated heads and measured heads.

In the subregional water budget (Table 4-3), discharge to wells was obtained as a residual of other estimates. As a check on this method, flow nets were established for each aquifer and Darcy's law was used to estimate horizontal flux toward discharge areas beneath the South Platte River. The differences between calculated flux and estimated discharge to wells was considered reasonable and was within the accuracy of transmissivity estimates used in the flux calculations. Results of the subregional water budget show that volumes of pumpage in the Arapahoe and Laramie/Fox Hills aquifers are similar. Pumpage from the Denver aquifer is significantly less than the other two bedrock aquifers.

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Table 4-1
Average Annual Water Budget for the Denver Groundwater Basin (1958–1978)*

Water Budget Component	Flow Rate (acre-feet/year)			
	Dawson Aquifer	Denver Aquifer	Arapahoe Aquifer	Laramie/Fox Hills Aquifer
Recharge	25,100	6,500	3,500	5,100
Leakage to overlying aquifer	---	4,800	8,200	0
Leakage to underlying aquifer	-4,800	-8,200	0	---
Discharge to surface deposits	-19,200	-1,700	-2,300	-2,800
Discharge to wells	-1,500	-3,300	-10,900	-3,000
Decline in storage	400	1,900	1,500	700

* From Robson, 1987 and Hurr, 1975

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Table 4-2
Groundwater Permits in the Vicinity of the Rocky Flats Site*

Map Reference Number[1]	Permit Number	Primary Use[2]	Geologic Aquifer[3]	Well Yield[4]	Well Depth	Water Level	Quarter	Section	Township	Range
1/1	33057F	M	KLF				NWSW	29	1S	69W
2/1	40239F	I	KLF	12	615		NWSW	29	1S	69W
3/1	6711F	I		4526	390		SWSW	29	1S	69W
4/1	15314	D		12	615	150	SWSW	29	1S	69W
5/1	15190MH	O	GW				NENE	30	1S	69W
6/1	35471F	M	KLF	23	790	160	NENE	30	1S	69W
7/1	15131MH	O	GW				NWNE	30	1S	69W
8/2	14317F	M	KLF	1	635	213	NWNE	30	1S	69W
8/2	35470F	M	KLF	23	897		NWNE	30	1S	69W
9/1	15469MH	O	GW				SENE	30	1S	69W
10/2	36155F	M	KLF	10	738	216	SENE	30	1S	69W
10/2	38794F	M	KLF	10	760	254	SENE	30	1S	69W
11/2	33059F	M	KLF				NENW	30	1S	69W
11/2	34319F	M	KLF				NENW	30	1S	69W
12/1	40241F	I	KLF	7	630		NENW	30	1S	69W
13/1	34318F	M	KLF				NWNW	30	1S	69W
14/1	25514	D		7	630	275	NWNW	30	1S	69W
15/1	8273	D		20	185	50	SENW	30	1S	69W
16/1	33060F	M	KLF				NESE	30	1S	69W
17/1	40237F	I	KLF		610		NESE	30	1S	69W
18/1	48196	D		15	610	200	NESE	30	1S	69W
19/1	15470MH	O	GW				NWSE	30	1S	69W
20/1	36154F	M	KLF	10	820	354	NWSE	30	1S	69W
21/1	44374	D		13	80	10	NENE	31	1S	69W
22/1	107719	D		7	675		NENW	31	1S	69W
23/1	108871	D					NWNW	31	1S	69W
24/1	119287	D					SWNW	31	1S	69W
25/1	34582	D		7	333	50	SWSE	31	1S	69W
26/1	33058F	M	KLF				NESW	31	1S	69W
27/1	40240F	I	KLF	25	800		NESW	31	1S	69W
28/1	113864	H	GW	7	740	329	NWSW	31	1S	69W
29/1	33061F	M	KLF				NWSW	31	1S	69W
30/1	40238F	I	KLF	25	800		NWSW	31	1S	69W
31/1	41362F	D	GW	7	740	329	NWSW	31	1S	69W
32/2	24243	D		25	800	220	SWSW	31	1S	69W
32/2	29289	D		25	800	215	SWSW	31	1S	69W
33/1	105681	H		6	725	360	NENE	32	1S	69W
34/1	115349	D					NENE	32	1S	69W
35/2	126082	D					NWNE	32	1S	69W
35/2	2600	D		10	410	200	NWNE	32	1S	69W
36/1	96127	H					NENW	32	1S	69W
37/1	100277	D		15	635	286	NENW	32	1S	69W
38/2	106022	D		8	600	120	NWNW	32	1S	69W
38/2	121149	D					NWNW	32	1S	69W
39/1	122045	D					SESW	32	1S	69W
40/1	12307	D		2	125	45	NENE	26	1S	70W

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Table 4-2
Groundwater Permits in the Vicinity of the Rocky Flats Site*

Map Reference Number[1]	Permit Number	Primary Use[2]	Geologic Aquifer[3]	Well Yield[4]	Well Depth	Water Level	Quarter	Section	Township	Range
41/1	173439	D	GW				NENW	26	1S	70W
42/1	173438	D	GW				NWNW	26	1S	70W
43/2	166530	D	GW				SENW	26	1S	70W
43/2	180084	D	GW				SENW	26	1S	70W
44/2	158002	D	GW				NESE	28	1S	70W
44/2	167982	D	GW				NESE	28	1S	70W
45/3	8817AD	C					NWSW	28	1S	70W
45/3	8577AD	C					NWSW	28	1S	70W
45/3	16207F	C		5	30	650	NWSW	28	1S	70W
46/7	9097	D	GW				NENW	29	1S	70W
46/7	101711	D	GW				NENW	29	1S	70W
46/7	1531	D		30	28	3	NENW	29	1S	70W
46/7	14644	D			35	10	NENW	29	1S	70W
46/7	14839	D		10	36	10	NENW	29	1S	70W
46/7	101711	D	GW	20	110	15	NENW	29	1S	70W
46/7	168705	D	GW	15	25		NENW	29	1S	70W
47/4	163191	H	GW				NENW	29	1S	70W
47/4	64128	H		7	40	6	NENW	29	1S	70W
47/4	68407	H		12	55	10	NENW	29	1S	70W
47/4	88897	H		7	50	15	NENW	29	1S	70W
48/1	146335	H	GW				NWNW	29	1S	70W
49/7	994	D		14	25	8	NWNW	29	1S	70W
49/7	11216	D		5	12	2	NWNW	29	1S	70W
49/7	40816	D		15	25	15	NWNW	29	1S	70W
49/7	43693	D		15	19	6	NWNW	29	1S	70W
49/7	50815	D		15	25	3	NWNW	29	1S	70W
49/7	61766	D		25	35	8	NWNW	29	1S	70W
49/7	62213	D		5	120	10	NWNW	29	1S	70W
50/4	40979	D	GW				SWNE	30	1S	70W
50/4	12640AD	D	GW				SWNE	30	1S	70W
50/4	18154	D		2	70	30	SWNE	30	1S	70W
50/4	35435	D		4526	35		SWNE	30	1S	70W
51/2	13248R	I		890	10	1	SWNE	30	1S	70W
51/2	13249R	I		225	30	5	SWNE	30	1S	70W
52/1	9418	D		4	52	20	SWNW	30	1S	70W
53/3	90564VE	D					NWSE	30	1S	70W
53/3	12722	D	GW	15	20		NWSE	30	1S	70W
53/3	112722	D	GW	6	450	150	NWSE	30	1S	70W
54/1	175606	D	GW	3	500	150	SESE	30	1S	70W
55/2	40979	D		12	98	6	SWSE	30	1S	70W
55/2	41712	D		3	100	8	SWSE	30	1S	70W
56/4	143713	D	GW				NESW	30	1S	70W
56/4	41320	D	GW				NESW	30	1S	70W
56/4	17831	D		3	215	95	NESW	30	1S	70W
56/4	41320	D		1.5	700	100	NESW	30	1S	70W
57/1	3240AD	O					NWSW	30	1S	70W

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Table 4-2
Groundwater Permits in the Vicinity of the Rocky Flats Site*

Map Reference Number[1]	Permit Number	Primary Use[2]	Geologic Aquifer[3]	Well Yield[4]	Well Depth	Water Level	Quarter	Section	Township	Range
58/4	120733	D					NWSW	30	1S	70W
58/4	3714	D		10	23	6	NWSW	30	1S	70W
58/4	36497	D		40	22	12	NWSW	30	1S	70W
58/4	128433	D		5	12		NWSW	30	1S	70W
59/6	148233	H	GW				NWSW	30	1S	70W
59/6	150433	H	GW				NWSW	30	1S	70W
59/6	150484	H	GW				NWSW	30	1S	70W
59/6	11554AD	H	GW				NWSW	30	1S	70W
59/6	150816	H	GW				NWSW	30	1S	70W
59/6	159380	H	GW				NWSW	30	1S	70W
60/1	146284	H	GW	1	65		NWNW	32	1S	70W
61/1	166624	S		1.5	200	43	NESW	32	1S	70W
62/1	2862	D		1	74	17	SWNW	33	1S	70W
63/1	88218	H					NWNE	34	1S	70W
64/1	15060	D		1	100	40	NWNE	36	1S	70W
65/1	130482	D					NESE	36	1S	70W
66/1	23878F	C					SENW	5	2S	69W
67/1	23590F	M					NENE	6	2S	69W
68/1	23591F	M					SWNE	6	2S	69W
69/1	28678F	M	KLF				SENW	6	2S	69W
70/1	28779	D		1	50	20	SWSW	6	2S	69W
71/1	9126	D		20	50	15	NENW	7	2S	69W
72/1	20133MH	OM	GW				NW	8	2S	69W
73/1	13494	D		20	142	75	SENE	17	2S	69W
74/1	33493F	C	LKA				NWNW	17	2S	69W
75/1	37404F	D	KLF				NWNW	17	2S	69W
76/1	33492F	C	KLF				SWNW	17	2S	69W
77/1	37405F	D	KLF				SWNW	17	2S	69W
78/1	15044R	N		5	182	90	SWNW	17	2S	69W
79/4	666	D	GW	10	95	10	NESE	17	2S	69W
79/4	955	D	GW	20	85	8	NESE	17	2S	69W
79/4	30030	D	GW	20	182	63	NESE	17	2S	69W
79/4	80021	D		15	300	150	NESE	17	2S	69W
80/2	168999	D	GW				SWNE	18	2S	69W
80/2	170163	H	LKA				SWNE	18	2S	69W
81/1	170724	D	KLF	20	1100	475	SWNE	18	2S	69W
82/1	21388F	C					NESE	18	2S	69W
83/2	29620	D		15	112	29	NESE	18	2S	69W
83/2	52028	D		8	122	44	NESE	18	2S	69W
84/1	96282	H		14	125	26	NESE	18	2S	69W
85/3	103583	D					SESE	18	2S	69W
	103583	D		15	125		SESE	18	2S	69W
85/3	132576	D					SESE	18	2S	69W
85/3	132563	D		5	10		SESE	18	2S	69W
86/1	132562	S		15	10		SESE	18	2S	69W
87/1	20769MH	OM	GW				SW	18	2S	69W

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Table 4-2
Groundwater Permits in the Vicinity of the Rocky Flats Site*

Map Reference Number[1]	Permit Number	Primary Use[2]	Geologic Aquifer[3]	Well Yield[4]	Well Depth	Water Level	Quarter	Section	Township	Range
88/13	26	D		15	125	40	NENE	19	2S	69W
88/13	122624	D					NENE	19	2S	69W
88/13	14820	D	GW				NENE	19	2S	69W
88/13	26	D		15	125	40	NENE	19	2S	69W
88/13	1246	D		15	67	6	NENE	19	2S	69W
88/13	8117	D		12	70	22	NENE	19	2S	69W
88/13	14820	D		8	70	12	NENE	19	2S	69W
88/13	18383	D		12	75	30	NENE	19	2S	69W
88/13	19069	D		6	100	16	NENE	19	2S	69W
88/13	32849	D		14	80	15	NENE	19	2S	69W
88/13	45855	D		15	110	15	NENE	19	2S	69W
88/13	89558	D		15	150	30	NENE	19	2S	69W
88/13	138834	D		15	71		NENE	19	2S	69W
89/2	104756	H					NENE	19	2S	69W
89/2	131220	H					NENE	19	2S	69W
90/1	131841	I					NENW	19	2S	69W
91/1	26942F	M	KLF				NENW	19	2S	69W
92/1	31058F	D	KLF				NENW	19	2S	69W
93/1	26730F	I					NWNW	19	2S	69W
94/2	26937F	M	KLF				NWNW	19	2S	69W
94/2	40582F	M	KLF	15	1024	390	NWNW	19	2S	69W
95/1	32349F	D	KLF				NWNW	19	2S	69W
96/1	161972	D	KA				NWSE	19	2S	69W
97/1	40003F	M	KLF				NWSE	19	2S	69W
98/3	32467	D		8	115	35	SESE	19	2S	69W
98/3	87059	D		5	140	30	SESE	19	2S	69W
98/3	139972	D		4	375	160	SESE	19	2S	69W
99/6	65747	D	LKA	13	202	65	SWSE	19	2S	69W
99/6	147077	D	KA				SWSE	19	2S	69W
99/6	223	D		6	110	10	SWSE	19	2S	69W
99/6	65747	D	GW	15	120	45	SWSE	19	2S	69W
99/6	93029VE	D	KA				SWSE	19	2S	69W
99/6	65747	D	LKA	13	202	65	SWSE	19	2S	69W
100/1	83981	D		5	305	100	SESW	19	2S	69W
101/3	15251	D		20	86	20	SWSW	19	2S	69W
101/3	15252	D	GW	20	86	20	SWSW	19	2S	69W
101/3	15252	D	LKA	14	125	42	SWSW	19	2S	69W
102/1	25429	D		4	40	4	SENE	20	2S	69W
103/1	142086	D	KA				NWSW	20	2S	69W
104/2	98697	D					SESW	20	2S	69W
104/2	85531	D		2.5	385	100	SESW	20	2S	69W
105/1	129919	H					SESW	20	2S	69W
106/4	163355	D	LKA	8	340	100	SWSW	20	2S	69W
106/4	556	D		20	185	35	SWSW	20	2S	69W
106/4	29754	D		20	240	45	SWSW	20	2S	69W
106/4	39001	D		15	170	41	SWSW	20	2S	69W

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Table 4-2
Groundwater Permits in the Vicinity of the Rocky Flats Site*

Map Reference Number[1]	Permit Number	Primary Use[2]	Geologic Aquifer[3]	Well Yield[4]	Well Depth	Water Level	Quarter	Section	Township	Range
107/2	167866	H	KA	6	325	100	SWSW	20	2S	69W
107/2	93051VE	H	GW				SWSW	20	2S	69W
108/5	82809	D					NWNE	29	2S	69W
108/5	25218	D		12	305	125	NWNE	29	2S	69W
108/5	52877	D		15	300	45	NWNE	29	2S	69W
108/5	54046	D		15	270	112	NWNE	29	2S	69W
108/5	63995	D		15	330	140	NWNE	29	2S	69W
109/2	66359	H		10	320	160	NWNE	29	2S	69W
109/2	75034	H		10	300	150	NWNE	29	2S	69W
110/1	151392	D	GW	15	60		SWNE	29	2S	69W
111/12	89392VE	H	LKA				NENW	29	2S	69W
111/12	91352VE	H	GW				NENW	29	2S	69W
111/12	114256	H					NENW	29	2S	69W
111/12	146760	H	KA				NENW	29	2S	69W
111/12	147318	H	TKD				NENW	29	2S	69W
111/12	147672	H	LKA				NENW	29	2S	69W
111/12	154769	H	GW				NENW	29	2S	69W
111/12	155357	H	GW	5	400	150	NENW	29	2S	69W
111/12	117329	H	KA	8	385	185	NENW	29	2S	69W
111/12	162724	H	LKA	13	380	172172	NENW	29	2S	69W
111/12	73870	H		10	300	100	NENW	29	2S	69W
111/12	82491	H		15	300	120	NENW	29	2S	69W
112/6	61192	D					NENW	29	2S	69W
112/6	11621	D	LKA	10	375	50	NENW	29	2S	69W
112/6	61192	D		14	300	100	NENW	29	2S	69W
112/6	81924	D		13	310	100	NENW	29	2S	69W
112/6	89110	D		3	296	80	NENW	29	2S	69W
112/6	178743	D	KLF	10	400	200	NENW	29	2S	69W
113/6	92234VE	D	GW				NWNW	29	2S	69W
113/6	66103	D	GW	15	300	50	NWNW	29	2S	69W
113/6	66103	D	KA	3.9	360	135	NWNW	29	2S	69W
113/6	37296	D		15	207	40	NWNW	29	2S	69W
113/6	66103	D	GW	1	320	150	NWNW	29	2S	69W
113/6	70958	D		12	340	140	NWNW	29	2S	69W
114/6	128355	H					NWNW	29	2S	69W
114/6	129190	H					NWNW	29	2S	69W
114/6	133829	H					NWNW	29	2S	69W
114/6	151850	H	GW	9	380	165	NWNW	29	2S	69W
114/6	73291	H		12	300	90	NWNW	29	2S	69W
114/6	76567	H		10	300	70	NWNW	29	2S	69W
115/1	14099	D		7	265	140	SWNW	29	2S	69W
116/2	2049	D		6	72	14	NESE	29	2S	69W
116/2	55735	D	GW	7	365		NESE	29	2S	69W
117/4	52998	D		15	300		NWSE	29	2S	69W
117/4	89233	D		7	175		NWSE	29	2S	69W
117/4	89234	D		12	110		NWSE	29	2S	69W

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Table 4-2
Groundwater Permits in the Vicinity of the Rocky Flats Site*

Map Reference Number[1]	Permit Number	Primary Use[2]	Geologic Aquifer[3]	Well Yield[4]	Well Depth	Water Level	Quarter	Section	Township	Range
117/4	93711	D		15	100		NWSE	29	2S	69W
118/3	137604	D	KA	15	650	280	SESE	29	2S	69W
118/3	139694	D					SESE	29	2S	69W
118/3	37262	D		15	427	245	SESE	29	2S	69W
119/1	45728	D		15	290	80	SWSE	29	2S	69W
120/1	31590	D		7	290	183	NESW	29	2S	69W
121/2	38217	D		25	315	150	NWSW	29	2S	69W
121/2	83110	D		12	310	147	NWSW	29	2S	69W
122/1	13803	D		2	80	25	SESW	29	2S	69W
123/4	23528	D		3	100	15	SWSW	29	2S	69W
123/4	33005	D		8	255	157	SWSW	29	2S	69W
123/4	40814	D		20	317	175	SWSW	29	2S	69W
123/4	70316	D		10	345	155	SWSW	29	2S	69W
124/1	2588	S		3	52	22	NENE	30	2S	69W
125/1	104321	H	GW	12	160	70	NWNE	30	2S	69W
126/1	126136	D					NWNW	30	2S	69W
127/3	1432	D		5	146	50	NWSE	30	2S	69W
127/3	15623	D		5	270	110	NWSE	30	2S	69W
127/3	36576	D		15	310	188	NWSE	30	2S	69W
128/3	18802F	C					SWSE	30	2S	69W
128/3	18801F	C					SWSE	30	2S	69W
128/3	18800F	C					SWSE	30	2S	69W
129/2	138155	D	KLF				SWSE	30	2S	69W
129/2	141979	D	KA				SWSE	30	2S	69W
130/1	138949	H	KA				SWSE	30	2S	69W
131/3	3798	D		12	165	80	NESW	30	2S	69W
131/3	50074	D		15	200	82	NESW	30	2S	69W
131/3	81301	D		4	331	110	NESW	30	2S	69W
132/1	18803F	C					SESW	30	2S	69W
133/1	129408	H					SESW	30	2S	69W
134/3	5357	D		10	180	90	SESW	30	2S	69W
134/3	12379	D		12	190	70	SESW	30	2S	69W
134/3	88807	D		11	225	80	SESW	30	2S	69W
135/5	160360	D	GW				SWSW	30	2S	69W
135/5	160360	D	KA	7	230	120	SWSW	30	2S	69W
135/5	10670	D		20	121	28	SWSW	30	2S	69W
135/5	95039	D	KLF	15	1060	190	SWSW	30	2S	69W
135/5	151567	D		15	140		SWSW	30	2S	69W
136/1	39352	S		15	195	103	SWSW	30	2S	69W
137/1	180634	OM	GW				SENE	1	2S	70W
138/4	18197MH	O	GW		73		SE	1	2S	70W
138/4	18357MHB	OM	GW				SESE	1	2S	70W
138/4	19249MH	OM	GW		175		SESE	1	2S	70W
138/4	167190	OM	GW		17		SESE	1	2S	70W
139/3	167188	OM	GW		12		SESW	1	2S	70W
139/3	180656	OM	GW				SESW	1	2S	70W

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Table 4-2
Groundwater Permits in the Vicinity of the Rocky Flats Site*

Map Reference Number[1]	Permit Number	Primary Use[2]	Geologic Aquifer[3]	Well Yield[4]	Well Depth	Water Level	Quarter	Section	Township	Range
139/3	181486	OM	GW				SESW	1	2S	70W
140/4	180947	OM	GW				SWSW	1	2S	70W
140/4	180635	OM	GW				SWSW	1	2S	70W
140/4	180640	OM	GW				SWSW	1	2S	70W
140/4	181766	OM	GW				SWSW	1	2S	70W
141/5	181215	OM	GW				NWNE	2	2S	70W
141/5	181213	OM	GW				NWNE	2	2S	70W
141/5	181460	OM	GW				NWNE	2	2S	70W
141/5	181223	OM	GW				NWNE	2	2S	70W
141/5	181545	OM	GW				NWNE	2	2S	70W
142/1	181256	OM	GW				SENE	2	2S	70W
143/1	18620MH	O	GW		1989		NENW	2	2S	70W
144/1	181769	OM	GW				NENW	2	2S	70W
145/1	181208	OM	GW				NWNW	2	2S	70W
146/1	18525MH	O	GW		52		SENW	2	2S	70W
147/7	18538MH	OM	GW				SENW	2	2S	70W
147/7	181218	OM	GW				SENW	2	2S	70W
147/7	181217	OM	GW				SENW	2	2S	70W
147/7	181202	OM	GW				SENW	2	2S	70W
147/7	181257	OM	GW				SENW	2	2S	70W
147/7	181225	OM	GW				SENW	2	2S	70W
147/7	181224	OM	GW				SENW	2	2S	70W
148/3	181216	OM	GW				NWSE	2	2S	70W
148/3	181222	OM	GW				NWSE	2	2S	70W
148/3	181765	OM	GW				NWSE	2	2S	70W
149/1	180636	OM	GW				SWSE	2	2S	70W
150/1	20017MH	OM	GW				SW	2	2S	70W
151/2	181823	OM	GW				NWSW	2	2S	70W
151/2	181201	OM	GW				NWSW	2	2S	70W
152/1	180920	OM	GW				SESW	2	2S	70W
153/3	18677MH	O	GW		175		SWSW	2	2S	70W
153/3	18695MH	O	GW				SWSW	2	2S	70W
153/3	19012MH	O	GW		56		SWSW	2	2S	70W
154/9	181746	OM	GW		33		SWSW	2	2S	70W
154/9	181454	OM	GW				SWSW	2	2S	70W
154/9	181246	OM	GW				SWSW	2	2S	70W
154/9	181245	OM	GW				SWSW	2	2S	70W
154/9	181770	OM	GW				SWSW	2	2S	70W
154/9	181104	OM	GW				SWSW	2	2S	70W
154/9	181109	OM	GW				SWSW	2	2S	70W
154/9	180637	OM	GW				SWSW	2	2S	70W
154/9	180638	OM	GW				SWSW	2	2S	70W
155/1	181214	OM	GW				NENE	3	2S	70W
156/1	18621MH	O	GW		200		SE	3	2S	70W
157/3	180698	OM	GW				NESE	3	2S	70W
157/3	181824	OM	GW				NESE	3	2S	70W

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Table 4-2
Groundwater Permits in the Vicinity of the Rocky Flats Site*

Map Reference Number[1]	Permit Number	Primary Use[2]	Geologic Aquifer[3]	Well Yield[4]	Well Depth	Water Level	Quarter	Section	Township	Range
157/3	181203	OM	GW				NESE	3	2S	70W
158/7	180627	OM	GW				SESE	3	2S	70W
158/7	180628	OM	KL				SESE	3	2S	70W
158/7	180629	OM	KL				SESE	3	2S	70W
158/7	180908	OM	GW				SESE	3	2S	70W
158/7	180907	OM	GW				SESE	3	2S	70W
158/7	180906	OM	GW				SESE	3	2S	70W
158/7	180905	OM	GW				SESE	3	2S	70W
159/1	180699	OM	GW				SWSE	3	2S	70W
160/1	181209	OM	GW				SESW	3	2S	70W
161/3	39572M	OM	GW				NENE	4	2S	70W
161/3	180946	OM	GW				NENE	4	2S	70W
161/3	180944	OM	GW				NENE	4	2S	70W
162/3	39570M	OM	GW				NWNE	4	2S	70W
162/3	39571M	OM	GW				NWNE	4	2S	70W
162/3	180945	OM	GW				NWNE	4	2S	70W
163/1	19390MH	OM	GW				NWNW	4	2S	70W
164/1	172507	C	GW				NWNW	4	2S	70W
165/3	32757M	O	GW				SWNW	4	2S	70W
165/3	32758M	O	GW				SWNW	4	2S	70W
165/3	32759M	O	GW				SWNW	4	2S	70W
166/1	3338	D		10	50		SENE	5	2S	70W
167/2	32717M	O	GW				SWNE	5	2S	70W
167/2	32716M	O	GW				SWNE	5	2S	70W
168/1	2651F	N	GW	100	18	5	SWNE	5	2S	70W
169/1	173643	D		1.35	502	250	NWSW	7	2S	70W
170/1	91184	H		15	105	40	SWSW	7	2S	70W
171/1	42120	D		20	200	5	NENE	8	2S	70W
172/2	18537MH	OM	GW	109			NESE	9	2S	70W
172/2	181558	OM	GW				NESE	9	2S	70W
173/2	180689	OM	GW				NWSE	9	2S	70W
173/2	181482	OM	GW				NWSE	9	2S	70W
174/2	180663	OM	GW				SESE	9	2S	70W
174/2	181563	OM	GW				SESE	9	2S	70W
175/2	180664	OM	GW				SWSE	9	2S	70W
175/2	180788	OM	GW				SWSE	9	2S	70W
176/1	11517AD	C	GW				NWSW	9	2S	70W
177/1	28915	S		2	18	8	NWSW	9	2S	70W
178/1	20016MH	OM	GW				NE	10	2S	70W
179/1	19013MH	O	GW		28		NENE	10	2S	70W
180/29	167418	OM	GW		30		NENE	10	2S	70W
180/29	167420	OM	GW		22		NENE	10	2S	70W
180/29	173709	OM	GW		24		NENE	10	2S	70W
180/29	173710	OM	GW		39		NENE	10	2S	70W
180/29	173711	OM	GW		69		NENE	10	2S	70W
180/29	173712	OM	GW		25		NENE	10	2S	70W

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Groundwater Permits in the Vicinity of the Rocky Flats Site*

Map Reference Number[1]	Permit Number	Primary Use[2]	Geologic Aquifer[3]	Well Yield[4]	Well Depth	Water Level	Quarter	Section	Township	Range
180/29	173713	OM	GW		46		NENE	10	2S	70W
180/29	173714	OM	GW		138		NENE	10	2S	70W
180/29	173715	OM	GW		30		NENE	10	2S	70W
180/29	173716	OM	GW		68		NENE	10	2S	70W
180/29	173717	OM	GW		22		NENE	10	2S	70W
180/29	173718	OM	GW		25		NENE	10	2S	70W
180/29	173719	OM	GW		28		NENE	10	2S	70W
180/29	173720	OM	GW		37		NENE	10	2S	70W
180/29	173722	OM	GW		35		NENE	10	2S	70W
180/29	173721	OM	GW		24		NENE	10	2S	70W
180/29	180630	OM	GW				NENE	10	2S	70W
180/29	181251	OM	GW				NENE	10	2S	70W
180/29	181458	OM	GW				NENE	10	2S	70W
180/29	181250	OM	GW				NENE	10	2S	70W
180/29	180708	OM	GW				NENE	10	2S	70W
180/29	180910	OM	GW				NENE	10	2S	70W
180/29	180909	OM	GW				NENE	10	2S	70W
180/29	180922	OM	GW				NENE	10	2S	70W
180/29	180921	OM	GW				NENE	10	2S	70W
180/29	180919	OM	GW				NENE	10	2S	70W
180/29	180792	OM	GW				NENE	10	2S	70W
180/29	180639	OM	GW				NENE	10	2S	70W
180/29	181497	OM	GW				NENE	10	2S	70W
181/1	180701	OM	GW				NWNE	10	2S	70W
182/1	19001MH	O	GW		138		SENE	10	2S	70W
183/5	180709	OM	GW				SENE	10	2S	70W
183/5	180648	OM	GW				SENE	10	2S	70W
183/5	180650	OM	GW				SENE	10	2S	70W
183/5	181480	OM	GW				SENE	10	2S	70W
183/5	181455	OM	GW				SENE	10	2S	70W
184/1	18753MH	O	GW				SWNE	10	2S	70W
185/4	181116	OM	GW				SWNE	10	2S	70W
185/4	181115	OM	GW				SWNE	10	2S	70W
185/4	181114	OM	GW				SWNE	10	2S	70W
185/4	181548	OM	GW				SWNE	10	2S	70W
186/1	180692	OM	GW				NWNW	10	2S	70W
187/1	180691	OM	GW				SENW	10	2S	70W
188/4	180679	OM	GW				SWNW	10	2S	70W
188/4	180693	OM	GW				SWNW	10	2S	70W
188/4	180697	OM	GW				SWNW	10	2S	70W
188/4	180662	OM	GW				SWNW	10	2S	70W
189/1	18910MH	O	GW				NESE	10	2S	70W
190/16	180715	OM	GW				NESE	10	2S	70W
190/16	180671	OM	GW				NESE	10	2S	70W
190/16	181464	OM	GW				NESE	10	2S	70W
190/16	181557	OM	GW				NESE	10	2S	70W

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Table 4-2
Groundwater Permits in the Vicinity of the Rocky Flats Site*

Map Reference Number[1]	Permit Number	Primary Use[2]	Geologic Aquifer[3]	Well Yield[4]	Well Depth	Water Level	Quarter	Section	Township	Range
190/16	181555	OM	GW				NESE	10	2S	70W
190/16	181119	OM	GW				NESE	10	2S	70W
190/16	181118	OM	GW				NESE	10	2S	70W
190/16	181113	OM	GW				NESE	10	2S	70W
190/16	181112	OM	GW				NESE	10	2S	70W
191/9	180714	OM	GW				NWSE	10	2S	70W
191/9	180661	OM	GW				NWSE	10	2S	70W
191/9	181544	OM	GW				NWSE	10	2S	70W
191/9	181111	OM	GW				NWSE	10	2S	70W
191/9	181235	OM	GW				NWSE	10	2S	70W
191/9	181561	OM	GW				NWSE	10	2S	70W
191/9	181472	OM	GW				NWSE	10	2S	70W
191/9	181554	OM	GW				NWSE	10	2S	70W
191/9	24349MH	OM	GW				NWSE	10	2S	70W
192/11	180700	OM	GW				SESE	10	2S	70W
192/11	180681	OM	GW				SESE	10	2S	70W
192/11	180682	OM	GW				SESE	10	2S	70W
192/11	180683	OM	GW				SESE	10	2S	70W
192/11	180903	OM	GW				SESE	10	2S	70W
192/11	180902	OM	GW				SESE	10	2S	70W
192/11	181120	OM	GW				SESE	10	2S	70W
192/11	180904	OM	GW				SESE	10	2S	70W
192/11	181556	OM	GW				SESE	10	2S	70W
192/11	181117	OM	GW				SESE	10	2S	70W
192/11	181536	OM	GW				SESE	10	2S	70W
193/1	18753MH	O	GW		30	23	SWSE	10	2S	70W
194/9	167191	OM	GW		160		SWSE	10	2S	70W
194/9	180666	OM	GW				SWSE	10	2S	70W
194/9	180678	OM	GW				SWSE	10	2S	70W
194/9	181481	OM	GW				SWSE	10	2S	70W
194/9	181479	OM	GW				SWSE	10	2S	70W
194/9	181541	OM	GW				SWSE	10	2S	70W
194/9	181539	OM	GW				SWSE	10	2S	70W
194/9	181538	OM	GW				SWSE	10	2S	70W
194/9	181537	OM	GW				SWSE	10	2S	70W
195/3	180690	OM	GW				NESW	10	2S	70W
195/3	181550	OM	GW				NESW	10	2S	70W
195/3	181465	OM	GW				NESW	10	2S	70W
196/4	181483	OM	GW				NWSW	10	2S	70W
196/4	181561	OM	GW				NWSW	10	2S	70W
196/4	181560	OM	GW				NWSW	10	2S	70W
196/4	181559	OM	GW				NWSW	10	2S	70W
197/2	181549	OM	GW				SESW	10	2S	70W
197/2	181540	OM	GW				SESW	10	2S	70W
198/1	181562	OM	GW				SWSW	10	2S	70W
199/2	17598MH	O	GW					10	2S	70W

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Table 4-2
Groundwater Permits in the Vicinity of the Rocky Flats Site*

Map Reference Number[1]	Permit Number	Primary Use[2]	Geologic Aquifer[3]	Well Yield[4]	Well Depth	Water Level	Quarter	Section	Township	Range
199/2	18267MH	O	GW		7		NENE	11	2S	70W
200/2	167187	OM	GW		10		NENE	11	2S	70W
200/2	180641	OM	GW				NENE	11	2S	70W
201/2	181234	OM	GW				NWNE	11	2S	70W
201/2	181462	OM	GW				NWNE	11	2S	70W
202/15	181134	OM	GW				SENE	11	2S	70W
202/15	181128	OM	GW				SENE	11	2S	70W
202/15	181127	OM	GW				SENE	11	2S	70W
202/15	181126	OM	GW				SENE	11	2S	70W
202/15	181133	OM	GW				SENE	11	2S	70W
202/15	181132	OM	GW				SENE	11	2S	70W
202/15	181137	OM	GW				SENE	11	2S	70W
202/15	181773	OM	GW				SENE	11	2S	70W
202/15	181138	OM	GW				SENE	11	2S	70W
202/15	181125	OM	GW				SENE	11	2S	70W
202/15	181124	OM	GW				SENE	11	2S	70W
202/15	181771	OM	GW				SENE	11	2S	70W
202/15	181461	OM	GW				SENE	11	2S	70W
202/15	181487	OM	GW				SENE	11	2S	70W
202/15	181496	OM	GW				SENE	11	2S	70W
203/8	181131	OM	GW				SWNE	11	2S	70W
203/8	181130	OM	GW				SWNE	11	2S	70W
203/8	181136	OM	GW				SWNE	11	2S	70W
203/8	181129	OM	GW				SWNE	11	2S	70W
203/8	181135	OM	GW				SWNE	11	2S	70W
203/8	180654	OM	GW				SWNE	11	2S	70W
203/8	181120	OM	GW				SWNE	11	2S	70W
203/8	181467	OM	GW				SWNE	11	2S	70W
204/1	1789MH	O	GW				NW	11	2S	70W
205/13	181233	OM	GW				NENW	11	2S	70W
205/13	181749	OM	GW				NENW	11	2S	70W
205/13	181232	OM	GW				NENW	11	2S	70W
205/13	181231	OM	GW				NENW	11	2S	70W
205/13	180642	OM	GW				NENW	11	2S	70W
205/13	180643	OM	GW				NENW	11	2S	70W
205/13	180644	OM	GW				NENW	11	2S	70W
205/13	180645	OM	GW				NENW	11	2S	70W
205/13	180646	OM	GW				NENW	11	2S	70W
205/13	180647	OM	GW				NENW	11	2S	70W
205/13	181521	OM	GW				NENW	11	2S	70W
205/13	181507	OM	GW				NENW	11	2S	70W
205/13	181499	OM	GW				NENW	11	2S	70W
206/1	19014MH	O	GW		27		NWNW	11	2S	70W
207/15	167421	OM	GW		12		NWNW	11	2S	70W
207/15	167419	OM	GW		31		NWNW	11	2S	70W
207/15	167422	OM	GW		12		NWNW	11	2S	70W

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Table 4-2
Groundwater Permits in the Vicinity of the Rocky Flats Site*

Map Reference Number[1]	Permit Number	Primary Use[2]	Geologic Aquifer[3]	Well Yield[4]	Well Depth	Water Level	Quarter	Section	Township	Range
207/15	180686	OM	GW				NWNW	11	2S	70W
207/15	180702	OM	GW				NWNW	11	2S	70W
207/15	181457	OM	GW				NWNW	11	2S	70W
207/15	181249	OM	GW				NWNW	11	2S	70W
207/15	181248	OM	GW				NWNW	11	2S	70W
207/15	181230	OM	GW				NWNW	11	2S	70W
207/15	180931	OM	GW				NWNW	11	2S	70W
207/15	180930	OM	GW				NWNW	11	2S	70W
207/15	181473	OM	GW				NWNW	11	2S	70W
207/15	181524	OM	GW				NWNW	11	2S	70W
207/15	181498	OM	GW				NWNW	11	2S	70W
208/26	181243	OM	GW				SENW	11	2S	70W
208/26	181242	OM	GW				SENW	11	2S	70W
208/26	181241	OM	GW				SENW	11	2S	70W
208/26	181240	OM	GW				SENW	11	2S	70W
208/26	181239	OM	GW				SENW	11	2S	70W
208/26	181238	OM	GW				SENW	11	2S	70W
208/26	181229	OM	GW				SENW	11	2S	70W
208/26	180713	OM	GW				SENW	11	2S	70W
208/26	180929	OM	GW				SENW	11	2S	70W
208/26	180928	OM	GW				SENW	11	2S	70W
208/26	180780	OM	GW				SENW	11	2S	70W
208/26	180784	OM	GW				SENW	11	2S	70W
208/26	180652	OM	GW				SENW	11	2S	70W
208/26	180653	OM	GW				SENW	11	2S	70W
208/26	181526	OM	GW				SENW	11	2S	70W
208/26	181525	OM	GW				SENW	11	2S	70W
208/26	181821	OM	GW				SENW	11	2S	70W
208/26	181522	OM	GW				SENW	11	2S	70W
208/26	181519	OM	GW				SENW	11	2S	70W
208/26	181547	OM	GW				SENW	11	2S	70W
208/26	181523	OM	GW				SENW	11	2S	70W
208/26	181500	OM	GW				SENW	11	2S	70W
208/26	181501	OM	GW				SENW	11	2S	70W
208/26	181468	OM	GW				SENW	11	2S	70W
208/26	181469	OM	GW				SENW	11	2S	70W
208/26	181466	OM	GW				SENW	11	2S	70W
209/1	19000MH	O	GW		152		SWNW	11	2S	70W
210/24	181244	OM	GW				SWNW	11	2S	70W
210/24	181456	OM	GW				SWNW	11	2S	70W
210/24	181750	OM	GW				SWNW	11	2S	70W
210/24	180710	OM	GW				SWNW	11	2S	70W
210/24	180649	OM	GW				SWNW	11	2S	70W
210/24	180787	OM	GW				SWNW	11	2S	70W
210/24	180782	OM	GW				SWNW	11	2S	70W
210/24	180651	OM	GW				SWNW	11	2S	70W

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Table 4-2
Groundwater Permits in the Vicinity of the Rocky Flats Site*

Map Reference Number[1]	Permit Number	Primary Use[2]	Geologic Aquifer[3]	Well Yield[4]	Well Depth	Water Level	Quarter	Section	Township	Range
210/24	181543	OM	GW				SWNW	11	2S	70W
210/24	181542	OM	GW				SWNW	11	2S	70W
210/24	181228	OM	GW				SWNW	11	2S	70W
210/24	181748	OM	GW				SWNW	11	2S	70W
210/24	181747	OM	GW				SWNW	11	2S	70W
210/24	181751	OM	GW				SWNW	11	2S	70W
210/24	181518	OM	GW				SWNW	11	2S	70W
210/24	181827	OM	GW				SWNW	11	2S	70W
210/24	181512	OM	GW				SWNW	11	2S	70W
210/24	181514	OM	GW				SWNW	11	2S	70W
210/24	181510	OM	GW				SWNW	11	2S	70W
210/24	181509	OM	GW				SWNW	11	2S	70W
210/24	181508	OM	GW				SWNW	11	2S	70W
210/24	181511	OM	GW				SWNW	11	2S	70W
210/24	24044MH	OM	GW				SWNW	11	2S	70W
210/24	181502	OM	GW				SWNW	11	2S	70W
211/1	17900MH	O	GW		10		SE	11	2S	70W
212/23	180983	OM	GW				NESE	11	2S	70W
212/23	180982	OM	GW				NESE	11	2S	70W
212/23	180981	OM	GW				NESE	11	2S	70W
212/23	180990	OM	GW				NESE	11	2S	70W
212/23	180991	OM	GW				NESE	11	2S	70W
212/23	180978	OM	GW				NESE	11	2S	70W
212/23	180962	OM	GW				NESE	11	2S	70W
212/23	181009	OM	GW				NESE	11	2S	70W
212/23	181008	OM	GW				NESE	11	2S	70W
212/23	181007	OM	GW				NESE	11	2S	70W
212/23	181006	OM	GW				NESE	11	2S	70W
212/23	181000	OM	GW				NESE	11	2S	70W
212/23	181096	OM	GW				NESE	11	2S	70W
212/23	181103	OM	GW				NESE	11	2S	70W
212/23	180789	OM	GW				NESE	11	2S	70W
212/23	180790	OM	GW				NESE	11	2S	70W
212/23	181108	OM	GW				NESE	11	2S	70W
212/23	181107	OM	GW				NESE	11	2S	70W
212/23	180791	OM	GW				NESE	11	2S	70W
212/23	180781	OM	GW				NESE	11	2S	70W
212/23	180658	OM	GW				NESE	11	2S	70W
212/23	181474	OM	GW				NESE	11	2S	70W
212/23	181139	OM	GW				NESE	11	2S	70W
213/59	180797	OM	GW				NWSE	11	2S	70W
213/59	180941	OM	GW				NWSE	11	2S	70W
213/59	180937	OM	GW				NWSE	11	2S	70W
213/59	180936	OM	GW				NWSE	11	2S	70W
213/59	180935	OM	GW				NWSE	11	2S	70W
213/59	180949	OM	GW				NWSE	11	2S	70W

Table 4-2
Groundwater Permits in the Vicinity of the Rocky Flats Site*

Map Reference Number[1]	Permit Number	Primary Use[2]	Geologic Aquifer[3]	Well Yield[4]	Well Depth	Water Level	Quarter	Section	Township	Range
213/59	180934	OM	GW				NWSE	11	2S	70W
213/59	180933	OM	GW				NWSE	11	2S	70W
213/59	180940	OM	GW				NWSE	11	2S	70W
213/59	180939	OM	GW				NWSE	11	2S	70W
213/59	180942	OM	GW				NWSE	11	2S	70W
213/59	180938	OM	GW				NWSE	11	2S	70W
213/59	180703	OM	GW				NWSE	11	2S	70W
213/59	180795	OM	GW				NWSE	11	2S	70W
213/59	180796	OM	GW				NWSE	11	2S	70W
213/59	180961	OM	GW				NWSE	11	2S	70W
213/59	180960	OM	GW				NWSE	11	2S	70W
213/59	180958	OM	GW				NWSE	11	2S	70W
213/59	180951	OM	GW				NWSE	11	2S	70W
213/59	180950	OM	GW				NWSE	11	2S	70W
213/59	180959	OM	GW				NWSE	11	2S	70W
213/59	180989	OM	GW				NWSE	11	2S	70W
213/59	180987	OM	GW				NWSE	11	2S	70W
213/59	180986	OM	GW				NWSE	11	2S	70W
213/59	180985	OM	GW				NWSE	11	2S	70W
213/59	180984	OM	GW				NWSE	11	2S	70W
213/59	180963	OM	GW				NWSE	11	2S	70W
213/59	181003	OM	GW				NWSE	11	2S	70W
213/59	181002	OM	GW				NWSE	11	2S	70W
213/59	180999	OM	GW				NWSE	11	2S	70W
213/59	180994	OM	GW				NWSE	11	2S	70W
213/59	180993	OM	GW				NWSE	11	2S	70W
213/59	180992	OM	GW				NWSE	11	2S	70W
213/59	181010	OM	GW				NWSE	11	2S	70W
213/59	181123	OM	GW				NWSE	11	2S	70W
213/59	181122	OM	GW				NWSE	11	2S	70W
213/59	181121	OM	GW				NWSE	11	2S	70W
213/59	181100	OM	GW				NWSE	11	2S	70W
213/59	180779	OM	GW				NWSE	11	2S	70W
213/59	181099	OM	GW				NWSE	11	2S	70W
213/59	181783	OM	GW				NWSE	11	2S	70W
213/59	181098	OM	GW				NWSE	11	2S	70W
213/59	181097	OM	GW				NWSE	11	2S	70W
213/59	181106	OM	GW				NWSE	11	2S	70W
213/59	181105	OM	GW				NWSE	11	2S	70W
213/59	180659	OM	GW				NWSE	11	2S	70W
213/59	181477	OM	GW				NWSE	11	2S	70W
213/59	181476	OM	GW				NWSE	11	2S	70W
213/59	181475	OM	GW				NWSE	11	2S	70W
213/59	181463	OM	GW				NWSE	11	2S	70W
213/59	181494	OM	GW				NWSE	11	2S	70W
213/59	181530	OM	GW				NWSE	11	2S	70W

Table 4-2
Groundwater Permits in the Vicinity of the Rocky Flats Site*

Map Reference Number[1]	Permit Number	Primary Use[2]	Geologic Aquifer[3]	Well Yield[4]	Well Depth	Water Level	Quarter	Section	Township	Range
213/59	181226	OM	GW				NWSE	11	2S	70W
213/59	181534	OM	GW				NWSE	11	2S	70W
213/59	181227	OM	GW				NWSE	11	2S	70W
213/59	181752	OM	GW				NWSE	11	2S	70W
213/59	181236	OM	GW				NWSE	11	2S	70W
213/59	181825	OM	GW				NWSE	11	2S	70W
213/59	181471	OM	GW				NWSE	11	2S	70W
214/3	180675	OM	GW				SESE	11	2S	70W
214/3	181493	OM	GW				SESE	11	2S	70W
214/3	181767	OM	GW				SESE	11	2S	70W
215/6	180957	OM	GW				SWSE	11	2S	70W
215/6	180956	OM	GW				SWSE	11	2S	70W
215/6	180955	OM	GW				SWSE	11	2S	70W
215/6	180954	OM	GW				SWSE	11	2S	70W
215/6	180977	OM	GW				SWSE	11	2S	70W
215/6	181101	OM	GW				SWSE	11	2S	70W
216/3	17899MH	O	GW		10		SW	11	2S	70W
216/3	18889MH	O	GW		159		SW	11	2S	70W
216/3	18911MH	O	GW		40		SW	11	2S	70W
217/26	181764	OM	GW				NESW	11	2S	70W
217/26	180953	OM	GW				NESW	11	2S	70W
217/26	180952	OM	GW				NESW	11	2S	70W
217/26	180971	OM	GW				NESW	11	2S	70W
217/26	180970	OM	GW				NESW	11	2S	70W
217/26	180969	OM	GW				NESW	11	2S	70W
217/26	180968	OM	GW				NESW	11	2S	70W
217/26	180967	OM	GW				NESW	11	2S	70W
217/26	180966	OM	GW				NESW	11	2S	70W
217/26	180965	OM	GW				NESW	11	2S	70W
217/26	181005	OM	GW				NESW	11	2S	70W
217/26	181004	OM	GW				NESW	11	2S	70W
217/26	181001	OM	GW				NESW	11	2S	70W
217/26	180998	OM	GW				NESW	11	2S	70W
217/26	180997	OM	GW				NESW	11	2S	70W
217/26	180996	OM	GW				NESW	11	2S	70W
217/26	180913	OM	GW				NESW	11	2S	70W
217/26	180927	OM	GW				NESW	11	2S	70W
217/26	180926	OM	GW				NESW	11	2S	70W
217/26	180925	OM	GW				NESW	11	2S	70W
217/26	180912	OM	GW				NESW	11	2S	70W
217/26	180660	OM	GW				NESW	11	2S	70W
217/26	181470	OM	GW				NESW	11	2S	70W
217/26	181490	OM	GW				NESW	11	2S	70W
217/26	181489	OM	GW				NESW	11	2S	70W
217/26	181488	OM	GW				NESW	11	2S	70W
218/1	19000MH	O	GW				NWSW	11	2S	70W

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Table 4-2
Groundwater Permits in the Vicinity of the Rocky Flats Site*

Map Reference Number[1]	Permit Number	Primary Use[2]	Geologic Aquifer[3]	Well Yield[4]	Well Depth	Water Level	Quarter	Section	Township	Range
219/7	180711	OM	GW				NWSW	11	2S	70W
219/7	180716	OM	GW				NWSW	11	2S	70W
219/7	180712	OM	GW				NWSW	11	2S	70W
219/7	181533	OM	GW				NWSW	11	2S	70W
219/7	181532	OM	GW				NWSW	11	2S	70W
219/7	181503	OM	GW				NWSW	11	2S	70W
220/35	164311	OM	GW				SESW	11	2S	70W
220/35	164312	OM	GW				SESW	11	2S	70W
220/35	164313	OM	GW				SESW	11	2S	70W
220/35	164314	OM	GW				SESW	11	2S	70W
220/35	164315	OM	GW				SESW	11	2S	70W
220/35	164316	OM	GW				SESW	11	2S	70W
220/35	164317	OM	GW				SESW	11	2S	70W
220/35	164318	OM	GW				SESW	11	2S	70W
220/35	164319	OM	GW				SESW	11	2S	70W
220/35	164320	OM	GW				SESW	11	2S	70W
220/35	164321	OM	GW				SESW	11	2S	70W
220/35	164322	OM	GW				SESW	11	2S	70W
220/35	164323	OM	GW				SESW	11	2S	70W
220/35	164324	OM	GW				SESW	11	2S	70W
220/35	180688	OM	GW				SESW	11	2S	70W
220/35	180911	OM	GW				SESW	11	2S	70W
220/35	180943	OM	GW				SESW	11	2S	70W
220/35	180704	OM	GW				SESW	11	2S	70W
220/35	180705	OM	GW				SESW	11	2S	70W
220/35	180706	OM	GW				SESW	11	2S	70W
220/35	180707	OM	GW				SESW	11	2S	70W
220/35	180964	OM	GW				SESW	11	2S	70W
220/35	181528	OM	GW				SESW	11	2S	70W
220/35	181756	OM	GW				SESW	11	2S	70W
220/35	181757	OM	GW				SESW	11	2S	70W
220/35	180923	OM	GW				SESW	11	2S	70W
220/35	180918	OM	GW				SESW	11	2S	70W
220/35	180793	OM	GW				SESW	11	2S	70W
220/35	180917	OM	GW				SESW	11	2S	70W
220/35	180672	OM	GW				SESW	11	2S	70W
220/35	180673	OM	GW				SESW	11	2S	70W
220/35	180674	OM	GW				SESW	11	2S	70W
220/35	181485	OM	GW				SESW	11	2S	70W
220/35	181484	OM	GW				SESW	11	2S	70W
220/35	181495	OM	GW				SESW	11	2S	70W
221/43	164337	OM	GW				SWSW	11	2S	70W
221/43	164338	OM	GW				SWSW	11	2S	70W
221/43	164339	OM	GW				SWSW	11	2S	70W
221/43	164340	OM	GW				SWSW	11	2S	70W
221/43	164341	OM	GW				SWSW	11	2S	70W

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Table 4-2
Groundwater Permits in the Vicinity of the Rocky Flats Site*

Map Reference Number[1]	Permit Number	Primary Use[2]	Geologic Aquifer[3]	Well Yield[4]	Well Depth	Water Level	Quarter	Section	Township	Range
221/43	164327	OM	GW				SWSW	11	2S	70W
221/43	164328	OM	GW				SWSW	11	2S	70W
221/43	164329	OM	GW				SWSW	11	2S	70W
221/43	164330	OM	GW				SWSW	11	2S	70W
221/43	164331	OM	GW				SWSW	11	2S	70W
221/43	164332	OM	GW				SWSW	11	2S	70W
221/43	164333	OM	GW				SWSW	11	2S	70W
221/43	164334	OM	GW				SWSW	11	2S	70W
221/43	164335	OM	GW				SWSW	11	2S	70W
221/43	164336	OM	GW				SWSW	11	2S	70W
221/43	180687	OM	GW				SWSW	11	2S	70W
221/43	180680	OM	GW				SWSW	11	2S	70W
221/43	180684	OM	GW				SWSW	11	2S	70W
221/43	180685	OM	GW				SWSW	11	2S	70W
221/43	181758	OM	GW				SWSW	11	2S	70W
221/43	181759	OM	GW				SWSW	11	2S	70W
221/43	181761	OM	GW				SWSW	11	2S	70W
221/43	181762	OM	GW				SWSW	11	2S	70W
221/43	181763	OM	GW				SWSW	11	2S	70W
221/43	181110	OM	GW				SWSW	11	2S	70W
221/43	181491	OM	GW				SWSW	11	2S	70W
221/43	181529	OM	GW				SWSW	11	2S	70W
221/43	181221	OM	GW				SWSW	11	2S	70W
221/43	181527	OM	GW				SWSW	11	2S	70W
221/43	181755	OM	GW				SWSW	11	2S	70W
221/43	181754	OM	GW				SWSW	11	2S	70W
221/43	181753	OM	GW				SWSW	11	2S	70W
221/43	180924	OM	GW				SWSW	11	2S	70W
221/43	180794	OM	GW				SWSW	11	2S	70W
221/43	180932	OM	GW				SWSW	11	2S	70W
221/43	180916	OM	GW				SWSW	11	2S	70W
221/43	180915	OM	GW				SWSW	11	2S	70W
221/43	181516	OM	GW				SWSW	11	2S	70W
221/43	180914	OM	GW				SWSW	11	2S	70W
221/43	180668	OM	GW				SWSW	11	2S	70W
221/43	180669	OM	GW				SWSW	11	2S	70W
221/43	180670	OM	GW				SWSW	11	2S	70W
221/43	180677	OM	GW				SWSW	11	2S	70W
222/4	167184	OM	GW		12		SENE	12	2S	70W
222/4	180948	OM	GW				SENE	12	2S	70W
222/4	180972	OM	GW				SENE	12	2S	70W
222/4	180633	OM	GW				SENE	12	2S	70W
223/1	180974	OM	GW				NENW	12	2S	70W
224/1	180655	OM	GW				NWNW	12	2S	70W
225/2	180973	OM	GW				SENW	12	2S	70W
225/2	180657	OM	GW				SENW	12	2S	70W

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Table 4-2
Groundwater Permits in the Vicinity of the Rocky Flats Site*

Map Reference Number[1]	Permit Number	Primary Use[2]	Geologic Aquifer[3]	Well Yield[4]	Well Depth	Water Level	Quarter	Section	Township	Range
226/5	180988	OM	GW				SWNW	12	2S	70W
226/5	180976	OM	GW				SWNW	12	2S	70W
226/5	180975	OM	GW				SWNW	12	2S	70W
226/5	181822	OM	GW				SWNW	12	2S	70W
226/5	180995	OM	GW				SWNW	12	2S	70W
227/1	18196MH	O	GW		10		SE	12	2S	70W
228/2	180632	OM	GW				NESE	12	2S	70W
228/2	181535	OM	GW				NESE	12	2S	70W
229/2	18357MH	OM	GW				SESE	12	2S	70W
229/2	167189	OM	GW				SESE	12	2S	70W
230/1	180676	OM	GW				NESW	12	2S	70W
231/2	180980	OM	GW				NWSW	12	2S	70W
231/2	180979	OM	GW				NWSW	12	2S	70W
232/1	18195MH	O	GW		12		NE	13	2S	70W
233/4	18356MH	OM	GW		10		SENE	13	2S	70W
233/4	167186	OM	GW		10		SENE	13	2S	70W
233/4	181258	OM	GW				SENE	13	2S	70W
233/4	180631	OM	GW				SENE	13	2S	70W
234/1	180785	OM	GW				NENW	13	2S	70W
235/1	181205	OM	GW				SENW	13	2S	70W
236/4	181206	OM	GW				SWNW	13	2S	70W
236/4	181505	OM	GW				SWNW	13	2S	70W
236/4	181504	OM	GW				SWNW	13	2S	70W
236/4	181237	OM	GW				SWNW	13	2S	70W
237/1	167185	OM	GW		13		NESE	13	2S	70W
238/1	181204	OM	GW				SESE	13	2S	70W
239/1	18336MH	O	GW		41		NE	14	2S	70W
240/2	181768	OM	GW				NENW	14	2S	70W
240/2	181506	OM	GW				NENW	14	2S	70W
241/2	164325	OM	GW				NWNW	14	2S	70W
241/2	164326	OM	GW				NWNW	14	2S	70W
242/1	18336MH	O	GW		175		SE	14	2S	70W
243/4	181207	OM	GW				NWSE	14	2S	70W
243/4	181459	OM	GW				NWSE	14	2S	70W
243/4	181517	OM	GW				NWSE	14	2S	70W
243/4	181546	OM	GW				NWSE	14	2S	70W
244/1	167192	OM	GW		44		SWSE	14	2S	70W
245/1	18335MH	O	GW				NE	15	2S	70W
246/3	181211	OM	GW				NENE	15	2S	70W
246/3	180667	OM	GW				NENE	15	2S	70W
246/3	180786	OM	GW				NENE	15	2S	70W
247/3	181210	OM	GW				NWNE	15	2S	70W
247/3	181253	OM	GW				NWNE	15	2S	70W
247/3	181252	OM	GW				NWNE	15	2S	70W
248/1	181212	OM	GW				SWNE	15	2S	70W
249/3	180665	OM	GW				NENW	15	2S	70W

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Table 4-2
Groundwater Permits in the Vicinity of the Rocky Flats Site*

Map Reference Number[1]	Permit Number	Primary Use[2]	Geologic Aquifer[3]	Well Yield[4]	Well Depth	Water Level	Quarter	Section	Township	Range
249/3	181492	OM	GW				NENW	15	2S	70W
249/3	181772	OM	GW				NENW	15	2S	70W
250/2	18512MH	OM	GW		49		SENW	15	2S	70W
250/2	180695	OM	GW				SENW	15	2S	70W
251/1	180694	OM	GW				SWNW	15	2S	70W
252/1	180696	OM	GW				NESW	15	2S	70W
253/4	181220	OM	GW				NWSW	15	2S	70W
253/44	181219	OM	GW				NWSW	15	2S	70W
253/4	181255	OM	GW				NWSW	15	2S	70W
253/4	181254	OM	GW				NWSW	15	2S	70W
254/2	18132F	C					NESE	16	2S	70W
254/2	17190F	C		150	604	6	NESE	16	2S	70W
255/1	12074AD	C	GW				SWSE	16	2S	70W
256/1	24781MH	OM	GW				NWNE	18	2S	70W
257/1	10467TH	O	GW		50	25	SENE	18	2S	70W
258/2	159199	D	GW				NWSW	18	2S	70W
258/2	178850	D	GW				NWSW	18	2S	70W
259/6	31869F	M	KD				NENW	19	2S	70W
259/6	31868F	M	KD				NENW	19	2S	70W
259/6	31870F	M	JM				NENW	19	2S	70W
259/6	31871F	M	JM				NENW	19	2S	70W
259/6	36077F	M	KD		1075	300	NENW	19	2S	70W
259/6	40627F	M	KD				NENW	19	2S	70W
260/2	37623F	D	KD	30	585	295	NENW	19	2S	70W
260/2	41727F	D	GW				NENW	19	2S	70W
261/1	72601	H			260		SENW	19	2S	70W
262/2	11877	D		6	325	45	SWNW	19	2S	70W
262/2	67546	D		7	253	50	SWNW	19	2S	70W
263/1	42737F	D	GW				SESE	19	2S	70W
264/1	45022	D		9	230	30	NWSW	19	2S	70W
265/1	28408	D		1	308	139	SESW	19	2S	70W
266/4	13018	D	GW	1	110	20	SWSW	19	2S	70W
266/4	33695	D		5	80	80	SWSW	19	2S	70W
266/4	35711	D		4526	410		SWSW	19	2S	70W
266/4	53597	D		6	200	43	SWSW	19	2S	70W
267/1	13439F	M		17	465	105	SWSW	19	2S	70W
268/1	3257	D		15	430	90	NWNE	21	2S	70W
269/11	40889M	OM	GW				NWSE	21	2S	70W
269/11	40890M	OM	GW				NWSE	21	2S	70W
269/11	40891M	OM	GW				NWSE	21	2S	70W
269/11	40892M	OM	GW				NWSE	21	2S	70W
269/11	40893M	OM	GW				NWSE	21	2S	70W
269/11	40882M	OM	GW				NWSE	21	2S	70W
269/11	40883M	OM	GW				NWSE	21	2S	70W
269/11	40887M	OM	GW				NWSE	21	2S	70W
269/11	40884M	OM	GW				NWSE	21	2S	70W

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Table 4-2
Groundwater Permits in the Vicinity of the Rocky Flats Site*

Map Reference Number[1]	Permit Number	Primary Use[2]	Geologic Aquifer[3]	Well Yield[4]	Well Depth	Water Level	Quarter	Section	Township	Range
269/11	40885M	OM	GW				NWSE	21	2S	70W
269/11	40888M	OM	GW				NWSE	21	2S	70W
270/2	40886M	OM	GW				SESE	21	2S	70W
270/2	40894M	OM	GW				SESE	21	2S	70W
271/1	40895M	OM	GW				SWSE	21	2S	70W
272/3	30549F	O	GW				SWSE	21	2S	70W
272/3	30550F	O	GW				SWSE	21	2S	70W
272/3	31885F	O	KLF				SWSE	21	2S	70W
273/1	33083F	O	GW				SWSW	21	2S	70W
274/1	23787F	C					NWNE	22	2S	70W
275/3	163334	OM	KA		50	33	NESE	22	2S	70W
275/3	163335	OM	KA		14	8	NESE	22	2S	70W
275/3	163336	OM	KA		11	8	NESE	22	2S	70W
276/1	10003F	N		30	1090		NESE	22	2S	70W
277/1	163333	OM	KA		60	53	NWSE	22	2S	70W
278/1	43208F	N	LKA				NESW	22	2S	70W
279/1	43207F	N	LKA				NWSW	22	2S	70W
280/2	131860	C					NESE	23	2S	70W
280/2	131861	C					NESE	23	2S	70W
281/1	34886M	O	GW				NESW	23	2S	70W
282/6	34892M	O	GW				SESW	23	2S	70W
282/6	34892M	O	GW				SESW	23	2S	70W
282/6	34892M	O	GW				SESW	23	2S	70W
282/6	34892M	O	GW				SESW	23	2S	70W
282/6	34892M	O	GW				SESW	23	2S	70W
282/6	34892M	O	GW				SESW	23	2S	70W
283/1	2679F	N		50	500	281	SWNE	24	2S	70W
284/1	20196	D		16	101	70	NWSE	24	2S	70W
285/1	34955	D		15	405	135	SESE	24	2S	70W
286/4	97839	D	GW				NENE	25	2S	70W
286/4	61190	D		2	320	100	NENE	25	2S	70W
286/4	97839	D		2	320	26	NENE	25	2S	70W
286/4	179656	D	KLF				NENE	25	2S	70W
287/2	34541	D			115	40	NWNE	25	2S	70W
287/2	35405	D		4526	100	60	NWNE	25	2S	70W
288/1	7548	D		30	1220	365	SENE	25	2S	70W
289/1	17967MH	O	GW	1	800	200	SWNE	25	2S	70W
290/1	34149	D		4526	80		NWNW	25	2S	70W
291/1	25117	D		20	190	95	NESE	25	2S	70W
292/4	17337	D		20	170	50	SESE	25	2S	70W
292/4	18722	D		22	1050	180	SESE	25	2S	70W
292/4	41313	D		25	1060	362	SESE	25	2S	70W
292/4	82199	D		8	28		SESE	25	2S	70W
293/1	9395AD	N					SWSE	25	2S	70W
294/1	37604	D		6	70	10	SWSE	25	2S	70W
295/1	4746	D		4526	200		NESW	25	2S	70W

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Table 4-2
Groundwater Permits in the Vicinity of the Rocky Flats Site*

Map Reference Number[1]	Permit Number	Primary Use[2]	Geologic Aquifer[3]	Well Yield[4]	Well Depth	Water Level	Quarter	Section	Township	Range
296/1	16705MH	O	GW				SESW	25	2S	70W
297/1	2925F	C		20	812	230	SESW	25	2S	70W
298/1	78493	S		15			SENW	26	2S	70W
299/1	34970	D		5	50	18	NESE	26	2S	70W
300/1	7619F	M		30	16	10	SESE	26	2S	70W
301/1	39737	D		20	30	17	SESE	26	2S	70W
302/1	33862F	O	KLF				SESW	26	2S	70W
303/2	2867F	C		550	715	260	SESW	26	2S	70W
303/2	13663F	C		160	862		SESW	26	2S	70W
304/1	33860F	O	KLF				SENW	27	2S	70W
305/1	24583F	C		20	879		SENW	27	2S	70W
306/1	2868F	C		600	784	300	NWSE	27	2S	70W
307/1	29564M	O		1	30		NWSW	27	2S	70W
308/2	18576MH	O	GW					28	2S	70W
308/2	16386MH	O	GW				NE	28	2S	70W
309/2	20576MH	OM	GW		37		NE	28	2S	70W
310/4	165127	OM	GW		68		NENE	28	2S	70W
310/4	165128	OM	GW		46		NENE	28	2S	70W
310/4	165129	OM	GW		59		NENE	28	2S	70W
310/4	165130	OM	GW		73		NENE	28	2S	70W
311/3	29572M	O	KLF	1	40		NWNE	28	2S	70W
311/3	29571M	O			35		NWNE	28	2S	70W
311/3	29573M	O			40		NWNE	28	2S	70W
311/3	165131	OM	GW		58		NWNE	28	2S	70W
312/3	165132	OM	GW		55		NWNE	28	2S	70W
312/3	165134	OM	GW		43		NWNE	28	2S	70W
313/6	40094M	OM	KLF		46		SENE	28	2S	70W
313/6	165125	OM	GW		15		SENE	28	2S	70W
313/6	165126	OM	GW		50		SENE	28	2S	70W
313/6	165133	OM	GW		44		SENE	28	2S	70W
313/6	177492	OM	GW		37		SENE	28	2S	70W
313/6	177493	OM	GW		37		SENE	28	2S	70W
314/1	29569M	O		1	30		SENE	28	2S	70W
315/5	40095M	OM	KLF		21		SWNE	28	2S	70W
315/5	40096M	OM	KLF		39		SWNE	28	2S	70W
315/5	177489	OM	GW				SWNE	28	2S	70W
315/5	177490	OM	GW		44		SWNE	28	2S	70W
315/5	177491	OM	GW		44		SWNE	28	2S	70W
316/1	29567M	O			44		SWNE	28	2S	70W
317/3	29565M	O	KLF	1	30		NESE	28	2S	70W
317/3	29568M	O	KLF	1	18		NESE	28	2S	70W
317/3	29565M	O	KLF	1	30		NESE	28	2S	70W
318/1	40093M	OM	KLF		47		NESE	28	2S	70W
319/2	26566M	O	KLF				NWSE	28	2S	70W
319/2	29566M	O		1	28		NWSE	28	2S	70W
320/6	40090M	OM	KLF		40		NWSE	28	2S	70W

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Table 4-2
Groundwater Permits in the Vicinity of the Rocky Flats Site*

Map Reference Number[1]	Permit Number	Primary Use[2]	Geologic Aquifer[3]	Well Yield[4]	Well Depth	Water Level	Quarter	Section	Township	Range
320/6	40091M	OM	KLF		45		NWSE	28	2S	70W
320/6	40092M	OM	KLF		47		NWSE	28	2S	70W
320/6	40879M	OM	GW				NWSE	28	2S	70W
320/6	40880M	OM	GW				NWSE	28	2S	70W
320/6	40881M	OM	GW				NWSE	28	2S	70W
321/1	29570M	O	KLF	1	30		SWSE	28	2S	70W
322/1	21762	D		20	50	4	SWSE	28	2S	70W
323/1	139259	D		15	30		SWSW	28	2S	70W
324/1	139260	S		5	18		SWSW	28	2S	70W
325/1	90532	H					SESE	29	2S	70W
326/1	139065	D	GW				NESW	29	2S	70W
327/1	150955	D	KD		1300		NWSW	29	2S	70W
328/2	139064	D					SESW	29	2S	70W
328/2	150566	D	KD				SESW	29	2S	70W
329/2	139556	D	GW				SWSW	29	2S	70W
329/2	153133	D	GW				SWSW	29	2S	70W
330/1	115658	D					NWNE	30	2S	70W
331/2	31673	D		15	500	300	NWNW	30	2S	70W
331/2	38979	D		10	230	146	NWNW	30	2S	70W
332/1	116029	D		3	715	127	SENW	30	2S	70W
333/1	146226	D	GW				NESE	30	2S	70W
334/3	107310	D					SESE	30	2S	70W
334/3	153132	D	GW				SESE	30	2S	70W
334/3	153134	D	GW				SESE	30	2S	70W
335/1	169807	H	GW				SESE	30	2S	70W

*From Colorado State Engineer's Office

[1]Numerator = Map Reference Number (see Plate 22)
Denominator = Number of wells associated with the map reference number

[2]Use codes for well permits:

I = Crop Irrigation
M = Municipal
C = Commercial
N = Industrial
D = Domestic
S = Stock
H = Household use only
O = Other
OM = Monitoring Well

[3]Geologic Aquifer Codes:

GW = All unnamed aquifers
KA = Arapaho
LKA = Lower Arapahoe
KD = Dakota
TKD = Denver
KLF = Laramie-Fox Hills
KL = Laramie
JM = Morrison

[4]Well yield in gpm (gallons per minute) (4526 = dry hole or no report)

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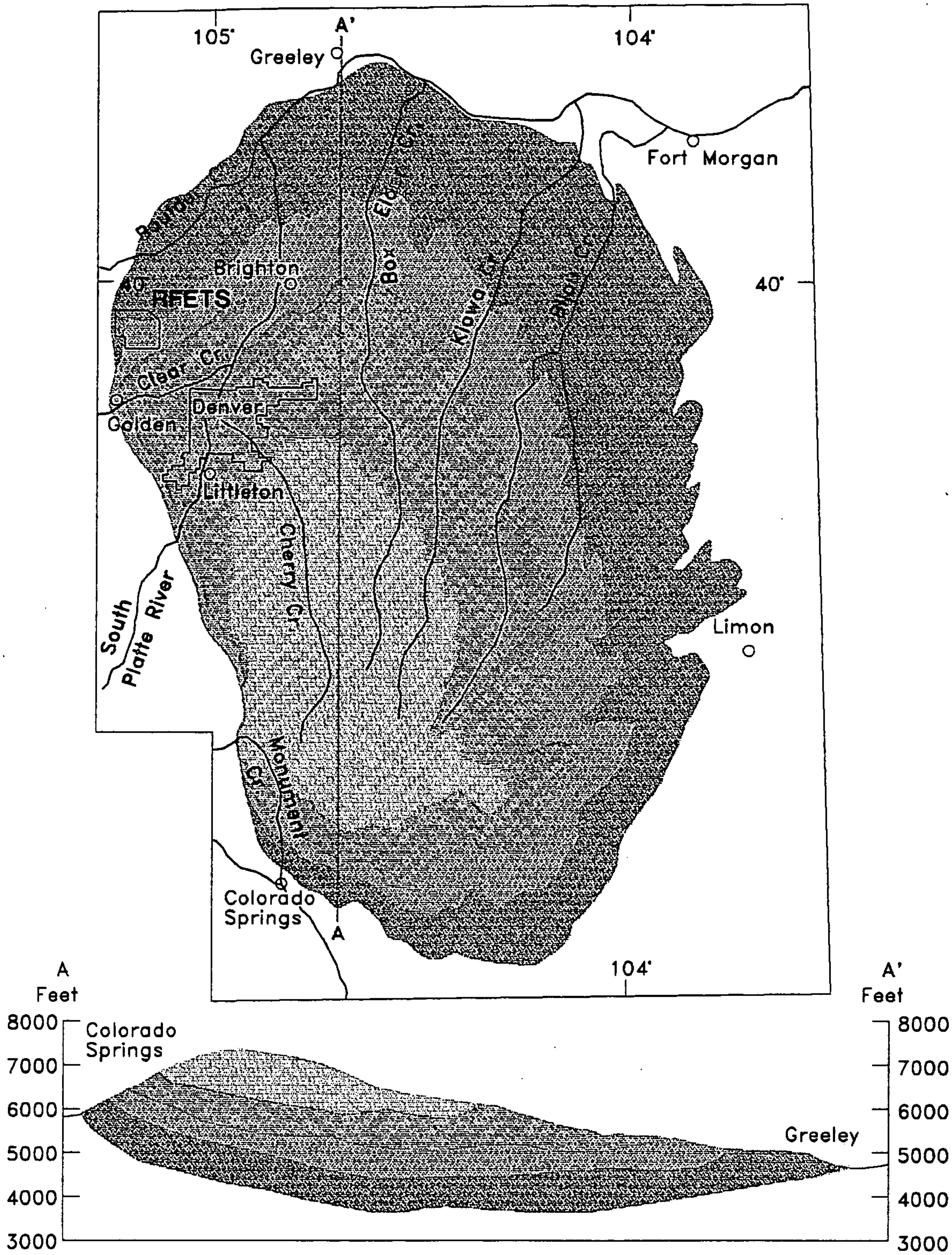
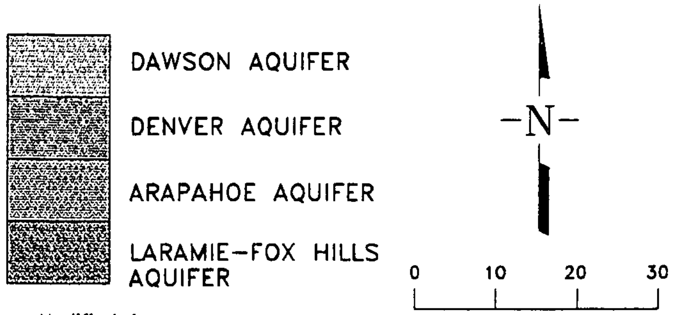
Table 4-3
Average Annual Water Budget for the Northwest Subregion of the Denver Groundwater Basin (1958–1978)*

Water Budget Component	Flow Rate (acre-feet/year)		
	Denver Aquifer	Arapahoe Aquifer	Laramie/Fox Hills Aquifer
Recharge	570	470	610
Leakage to overlying aquifer	-350	0	---
Leakage to underlying aquifer	---	350	0
Discharge to alluvium	0	0	0
Discharge to wells	-190	-650	-730
Decline in storage	-30	-170	120

* From Robson, 1987 and Hurr, 1975





Modified from Robson (1987)

EG&G ROCKY FLATS
Rocky Flats Site, Golden, Colorado

LOCATION AND EXTENT OF BEDROCK AQUIFERS IN THE DENVER GROUNDWATER BASIN

Hydrogeologic Characterization Report

Date April 1995	Figure 4–1

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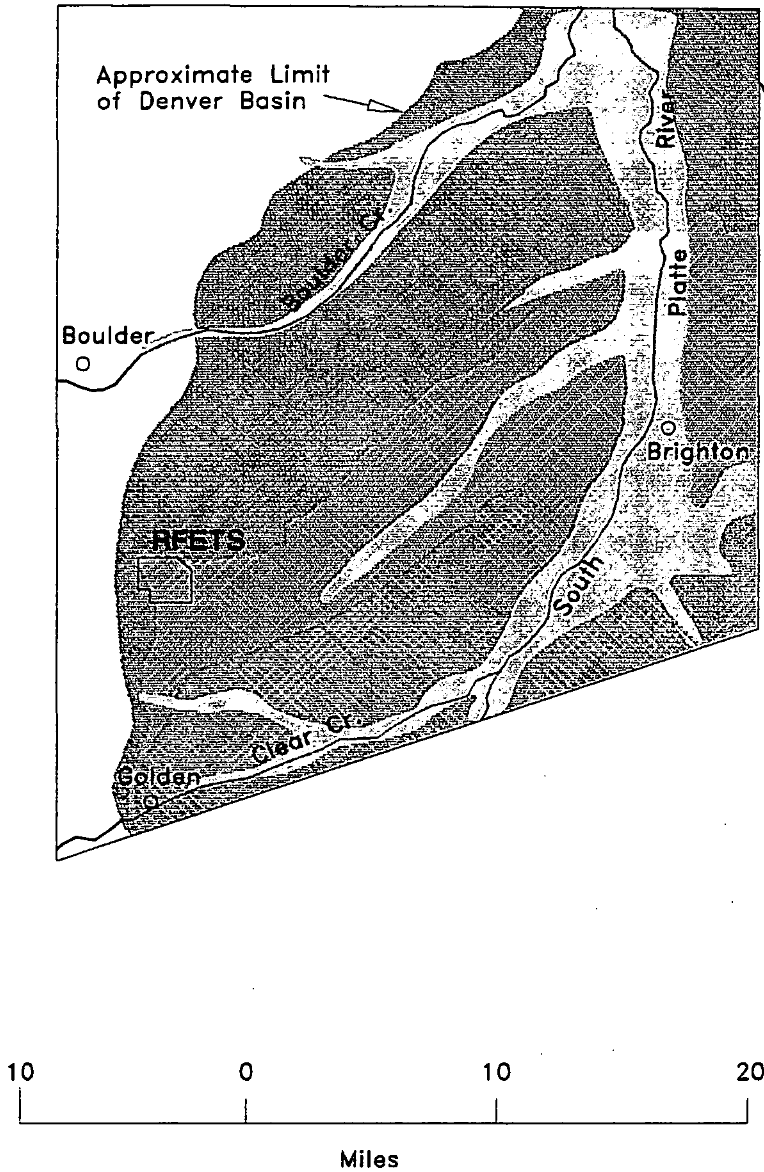
Best Available Copy



Qp	Regional Alluvial Aquifer
Tkd	Denver Aquifer
Tka	Aparahoe Aquifer
Tklfh	Laramie–Fox Hills Aquifer

–N–

Scale: 1: 500,000

Modified from Norris and Others (1985), Robson and Others (1981a and 1981b), and Robson (1983).

EG&G ROCKY FLATS
Rocky Flats Site, Golden, Colorado

APPROXIMATE AREAL EXTENT OF BEDROCK AQUIFER AND MAJOR ALLUVIAL AQUIFER, NORTHWEST SUBREGION OF THE DENVER GROUNDWATER BASIN

Hydrogeologic Characterization Report

Date April 1995 | Figure 4–2

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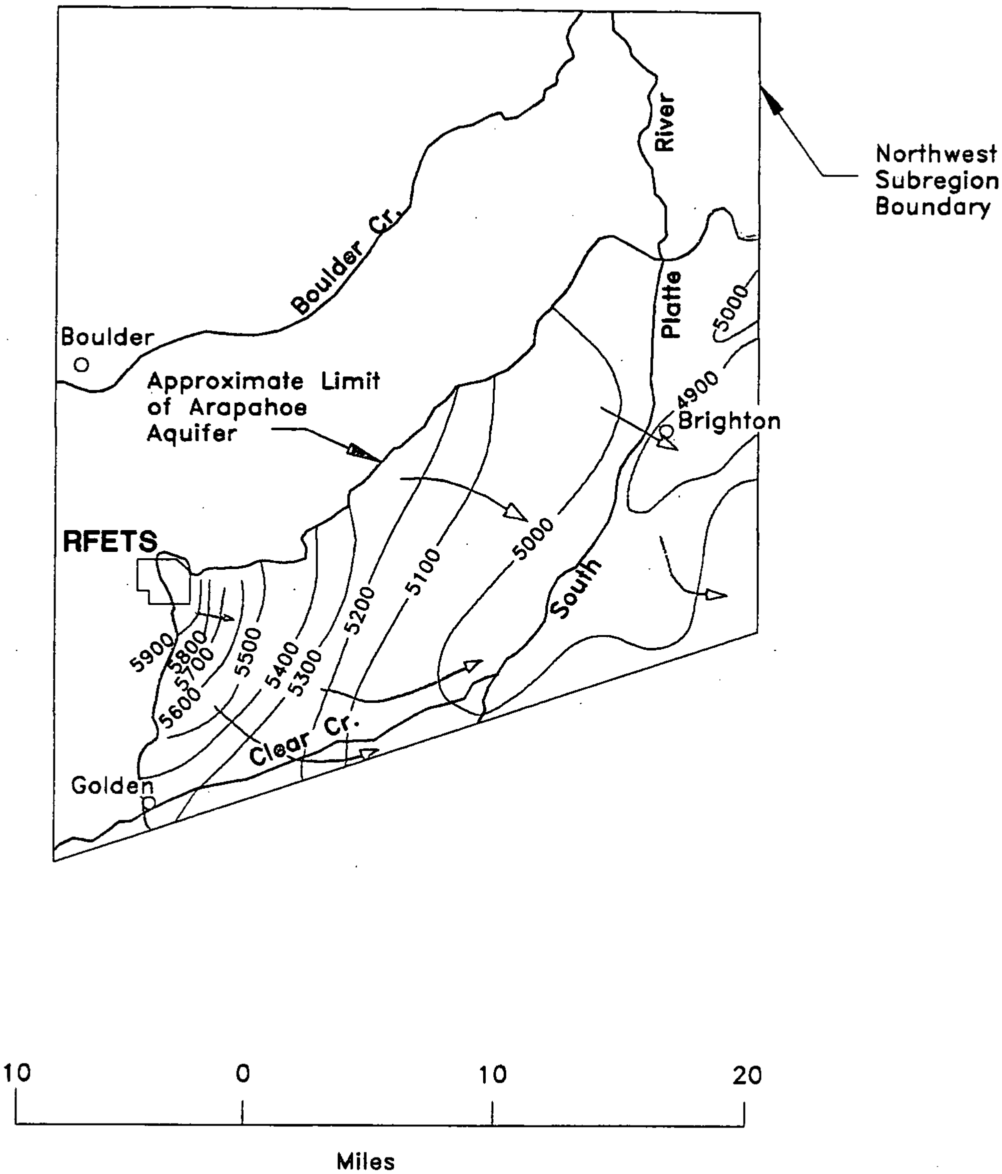


-5000- Potentiometric Surface Contour and Groundwater Elevation (Nation Geodetic Vertical Datum of 1929) Contour Interval 100 feet

Approximate direction of Groundwater Flow

-N-

Scale: 1: 500,000

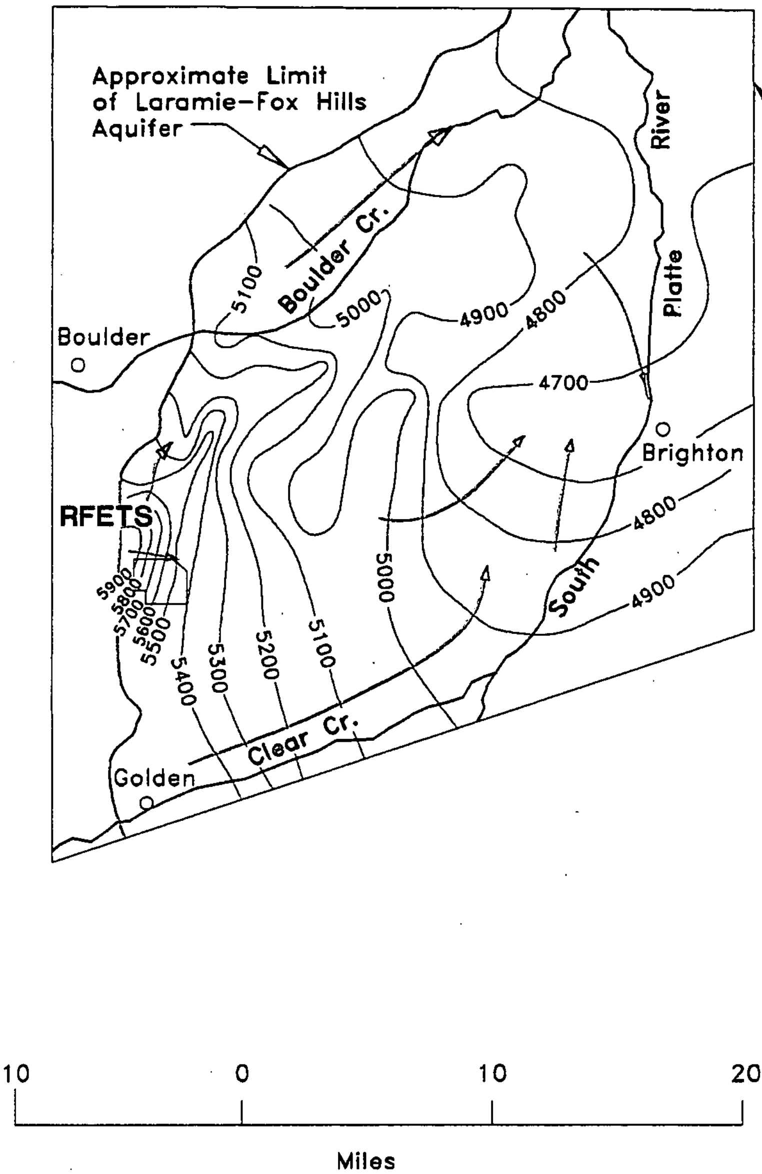
Modified from Robson and Others (1981a)

EG&G ROCKY FLATS
Rocky Flats Site, Golden, Colorado

POTENTIOMETRIC SURFACE OF THE ARAPAHOE AQUIFER IN THE NORTHWEST SUBREGION OF THE DENVER GROUNDWATER BASIN

Hydrogeologic Characterization Report

Date April 1995	Figure 4-3



5000 Potentiometric Surface Contour and Groundwater Elevation (Nation Geodetic Vertical Datum of 1929) Contour Interval 100 feet

Approximate direction of Groundwater Flow

N

Scale: 1: 500,000

Modified from Robson (1981b)

EG&G ROCKY FLATS
Rocky Flats Site, Golden, Colorado

POTENTIOMETRIC SURFACE OF THE LARAMIE-FOX HILLS AQUIFER IN THE NORTHWEST SUBREGION OF THE DENVER GROUNDWATER BASIN

Hydrogeologic Characterization Report

Date April 1995	Figure 4-4

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5. Sitewide Groundwater Program Activities

5.1 Groundwater Monitoring Program

Groundwater monitoring is an essential function of groundwater contamination investigations and facility regulatory compliance. It is also an important component of ongoing sitewide hydrogeologic characterization efforts at the Rocky Flats site. Groundwater monitoring operations at the Rocky Flats site support a variety of programs which have been designed and implemented to assess potential and existing contaminant releases from CERCLA and RCRA Operable Units, underground storage tanks, and the new sanitary landfill. In addition, monitoring programs exist for evaluating the effectiveness or stability of engineered structures, such as dams and French drains, and assessing hydrologic processes, such as surface/groundwater interactions and groundwater recharge. The majority of wells are monitored and serviced by the Environmental Operations Management, Hydrogeologic Operations Group, which coordinates sampling and well abandonment activities for Environmental Restoration projects. Certain specialty monitoring programs, such as dam piezometer water level measurements, are conducted by other plant organizations. Details of the Rocky Flats site Groundwater Monitoring Program are presented more fully in the Groundwater Protection and Monitoring Program Plan (EG&G, 1993h).

5.1.1 Well Nomenclature and Classification

Standardization of well names at the Rocky Flats site was initiated in 1992 to eliminate the inconsistent and often confusing usage of historical well numbers and coordinate the naming of new wells. By convention, the majority of monitoring well names are designated using a four- to seven-digit location code starting with a well number followed by a two-digit year code. A five-digit code adopted in 1991 currently defines the only approved name for new wells installed at the Rocky Flats site. Rules for well names apply as follows:

- Pre-1986 - Variable numeric and alphanumeric, although the majority involve a four-digit numeric location code consisting of two-digit well number followed by year (i.e., well 1474)
- 1986 to 1988 - Four-digit numeric location code consisting of two-digit well number followed by year (i.e., well 1787).
- 1989 - Seven-digit alphanumeric location code consisting of, from left to right, the well type (B = buffer zone, P = plant); plant quadrant location (1 through 4), a three-digit well number and two-digit year code (i.e., well B410589). Typically, only the last five-digits are used for sequentially ordering well names in this group

- 1990 - Four-digit numeric location code consisting of two-digit well number followed by year (i.e., 0790).

- 1991 to present - Five-digit numeric location code consisting of three-digit well number followed by year (i.e., well 45191).

Exceptions to this system are known to occur, but typically involve historical wells or wells installed for non-monitoring purposes (i.e., CW001 OU1 production well). The known alias location codes for each well are shown in Appendix B.

The groundwater monitoring network at the Rocky Flats site comprises the following seven categories of monitoring wells as shown on Plate 3-1 of EG&G (1995a) and Appendix B to this report:

1. RCRA-S: RCRA-required wells used for calculating statistics for comparisons of groundwater quality. Sampled and analyzed as specified in the Final Groundwater Assessment Plan (DOE, 1993a) and any subsequent approved changes.

2. RCRA-C: RCRA-required wells used for determining "the rate and extent of migration of hazardous wastes or hazardous waste constituents in the groundwater." Sampled and analyzed as specified in the Final Groundwater Assessment Plan (DOE, 1993a) and any subsequently approved changes.

3. CERCLA: CERCLA-required wells used for characterizing groundwater at Rocky Flats operable units. Sampled and analyzed as specified in the applicable CERCLA RI work plans and any subsequently approved changes.

4. Boundary-AIP: CDPHE-required wells used for monitoring groundwater at downgradient Rocky Flats site boundaries. Sampled and analyzed as specified in the Agreement in Principal (DOE, 1989a) and any subsequently approved changes.

5. Plant Protection: Wells proposed for semi-annual sampling and analysis used to monitor groundwater at Rocky Flats for source characterization or plume definition. To be sampled and analyzed in accordance with Groundwater Monitoring Plan for Rocky Flats (EG&G, 1994c) and any subsequently approved changes.

6. New Landfill: CDPHE-required wells for permitting the new landfill. To be sampled and analyzed as specified in the Groundwater Monitoring Plan for the New Sanitary Landfill (EG&G, 1993d) and any subsequently approved changes.

7. Non-GMP: Wells installed for engineering or other special purposes that are not members of any of the well classes listed above.

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As of the fourth quarter 1994, the following number of wells and piezometers were being monitored by well type:

RCRA-S	40
RCRA-C	58
CERCLA	144
Boundary-AIP	10
Plant Protection	151
New Landfill	4
Non-GMP	83
Total	490

Monitoring wells are also categorized according to whether or not the well is active, inactive, or abandoned as of the published date of the map, with specific reference to Groundwater Monitoring Program (GMP) operations. Active wells represent those wells that are regularly monitored for groundwater samples and water levels in support of specific characterization or regulatory compliance programs. An inactive status identifies those wells that are not currently monitored by the GMP on a regular basis. These wells, however, may be monitored for specific applications which occur outside of the scope of normal GMP operations. Wells shown as abandoned have been physically removed or plugged under the Well Abandonment and Replacement Program. Plate 1 shows the current groundwater monitoring network at the Rocky Flats site. A summary of the active status of wells is provided in Table 5-1.

5.1.2 Early Monitoring Well Networks (1954 to 1985)

Groundwater monitoring has been conducted at the Rocky Flats site since the first groundwater monitoring wells were installed in 1954. Until 1974, early groundwater monitoring activities focused primarily on the detection of selected radionuclide and major ion constituents (e.g., pH, nitrate, fluoride) at the Solar Evaporation Pond area (Boss, 1973). The monitoring program was expanded in 1974 in conjunction with DOE and USGS efforts to characterize the hydrology of the site (Hurr, 1976). Additional wells were installed in 1981 and 1982 as part of the first RCRA Groundwater Monitoring Plan. In most cases wells installed prior to 1986 have been abandoned or scheduled for abandonment because of concerns involving well construction and/or inadequate documentation. Details regarding the abandonment status and construction of these wells is provided in Appendix B.

Although groundwater monitoring has been historically conducted entirely within the plant boundary, a limited amount of water quality information has been collected by the

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Rocky Flats site from surrounding domestic and production wells completed in the Laramie/Fox Hills and Dawson aquifers (Illsley, written communication, 1976). Seven bedrock wells, ranging in depth from 260 to 1220 feet, were sampled for plutonium, uranium, tritium, pH, total dissolved solids, and major anions in December 1975. The results of testing indicated that there was no significant difference between up and downgradient water quality and that the wells were free of radionuclide contaminants.

5.1.3 Current Monitoring Well Network (1986 to Present)

Table 5-1 clearly indicates that the majority of wells were installed after 1985 with most still in service. Of the 490 wells currently monitored, 366 are being sampled with associated water-level measurements, and the remaining 124 wells are monitored only for water levels. Plate 1 shows the location of all active groundwater monitoring wells as of December 1, 1994, with four exceptions. These include monitoring wells 46192 and 46292, which were installed downstream of the earthen dams that form Great Western Reservoir and Standley Reservoir, respectively, and monitoring wells 11894 and 11994, which are located along Walnut Creek between Indiana Street and Great Western Reservoir. The clustered configuration of monitoring wells in the central plant area is largely determined by individual potential contaminant source area investigations, such as depicted by the Solar Evaporation Pond, OU1 and OU2 areas, and the stage at which these investigations have attained. Monitoring wells in the Buffer Zone, especially wells installed in 1989 and 1990 south of Woman Creek and north of McKay Ditch, provide information on background groundwater conditions. Additional Buffer Zone wells drilled in 1994 under the Well Abandonment and Replacement Program (WARP) (not shown on Plate 3-1) will serve to further delineate groundwater conditions in surficial alluvial materials both upgradient and downgradient of the plant area.

The monitoring well network undergoes constant evaluation to determine the most effective approach to monitoring groundwater. This evaluation takes into account current regulations; recent developments in groundwater monitoring technology; and individual project monitoring requirements to streamline the program in a manner that assures the collection of adequate and technically valid data while preventing program excesses. The evaluation is accomplished through a variety of means, including such tools as an annual well evaluation report, self auditing and a sample request process.

5.1.4 Well Construction

Appendix B summarizes information concerning the well type, location, surface elevation, construction and completion details, and well status of known monitoring wells installed at the Rocky Flats site since 1954. A brief discussion of additional well construction practices by year is provided below.

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5.1.4.1 Pre-1986 Wells

Fifty-six monitoring wells were installed between 1960 and 1982. Unfortunately, well completion information available for these wells is incomplete or of variable quality. Consideration of the uncertainties associated with pre-1986 well construction is critical to any evaluation of the early well data. These uncertainties generally fall into one or more of the following three categories:

1. a lack of well completion information, usually involving intake interval or annular seals,
2. missing or inadequate geologic logs, and
3. improper well construction materials for groundwater sampling.

Currently, all of the pre-1986 wells have either already been abandoned or are scheduled for abandonment in calendar year 1995.

5.1.4.2 1986 Wells

During 1986, a total of 52 alluvial, 17 bedrock, and one alluvial/bedrock wells were installed. The wells were constructed with a 2-inch diameter, 316-grade stainless steel casing, and a wire-wrapped stainless steel screen with a 0.020- or 0.010-inch opening. Mesh size 12-20 Colorado Silica Sand was used as filter pack to fill the annulus between the well screen and the borehole walls when the 0.020-inch opening screen was used. Mesh size 16-40 or 32-42 Colorado Silica Sand was used with the 0.010-inch well screens. Sumps were not installed below the screen. Screens were cut to length and welded to the solid riser (Rockwell International, 1986a).

The alluvial wells were screened 5 feet above the static water level encountered at the time of drilling. This allowed for seasonal variations in the water table. In both alluvial and bedrock wells, the filter-pack was extended approximately 2 feet above the screened interval. A bentonite pellet seal, a minimum of 1 foot thick, was placed above the filter-pack. The annular space above the bentonite seal was cemented to the ground surface with cement grout containing 5 percent bentonite. A steel protective casing with a locking cover was installed immediately after the well was installed. A concrete surface pad designed to deflect surface water away from the well was installed within two weeks of the grouting operations (Rockwell International, 1986a). Forty-nine of the 70 monitoring wells installed in 1986 are being sampled. The remainder of these wells are inactive and are currently being evaluated for abandonment.

5.1.4.3 1987 Wells

During 1987, 45 alluvial, 22 bedrock, and one alluvial/bedrock wells were installed. The wells were constructed of a 2-inch diameter, 316-grade, stainless-steel casing, and a wire-wrapped stainless-steel screen with a 0.010-inch opening. Mesh size 32-42

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Colorado Silica Sand was used to fill the annulus between the well casing and the borehole wall. All screens were custom-cut and welded to the solid riser casing. Sumps were not installed below the screen. Well design and drilling methods were consistent with those used during well installation in 1986 (DOE, 1987). Forty of the 67 monitoring wells installed in 1987 are being sampled. The remainder of these wells are measured for water level and are currently being evaluated for abandonment.

5.1.4.4 1988 Wells

During 1988, 10 alluvial piezometers were installed. All were constructed of 1-inch diameter schedule 40 polyvinylchloride (PVC). No other construction information is currently available. These piezometers were installed to determine depth to water along the route of a proposed corridor for a buried electrical utility line.

5.1.4.5 1989 Wells

During 1989, 95 alluvial and 67 bedrock wells were installed. The alluvial wells were constructed of 4-inch diameter schedule 40 PVC. The piezometers and bedrock wells shallower than 100 feet were constructed of 2-inch diameter schedule 40 PVC. Bedrock wells deeper than 100 feet were constructed of 2-inch schedule 80 PVC. The use of PVC resulted in reduced well installation costs and allowed increased well casing diameter to facilitate sampling. Both alluvial and bedrock wells were constructed with 0.010-inch screens. Mesh size 16-40 Colorado Silica Sand was used to fill the annulus between the well casing and the borehole wall. One-foot sumps were installed below the screen, and all casing and screen were threaded flush-joints. Well design and drilling methods were consistent with those used during well installation in 1986 and 1987 (Rockwell International, 1987).

5.1.4.6 1990 Wells

During 1990, 17 alluvial wells and piezometers were installed. Thirteen wells were installed during the New Sanitary Landfill (NSL) siting evaluation. These wells were completed with 2-inch diameter schedule 40 PVC casing and 0.010-inch screens. Three of the thirteen wells were installed with mesh size 16-40 filter-packs and 10 were installed with mesh size 8-12 filter-packs (Merrick, 1991).

Four French Drain geotechnical investigation piezometers were installed at OU1. Two were installed with 2-inch diameter schedule 40 PVC casing and two were installed with a 2-inch diameter schedule 80 PVC casing with 0.010-inch screens and mesh size 16-40 filter-packs (EG&G, 1990a).

5.1.4.7 1991 Wells

These wells were installed for OU1 and OU2 characterization and for sitewide characterization. During 1991, 87 alluvial wells, 6 alluvial/bedrock wells, and 46 bedrock wells were installed. All wells were constructed of 2-inch diameter schedule 40 PVC. Well screens were installed with 0.010-inch factory-cut slots and mesh size 16-40 silica sand was used as filter-pack. Two-foot sumps were installed below the well screens.

5.1.4.8 1992 Wells

These wells were installed for a continuation of hydrogeologic characterization in the OU1, OU2, and OU5 areas. During 1992, 26 alluvial wells and 12 bedrock wells were installed. All wells were constructed of 2-inch diameter schedule 40 PVC. Wells screens were installed with 0.010-inch factory-cut slots and mesh size 16-40 silica sand was used as filter-pack. Two-foot sumps were installed below the well screens.

5.1.4.9 1993 Wells

These wells were installed for characterization in OU4, OU5, OU6, and OU7 areas. During 1993, 116 alluvial wells, 15 alluvial/bedrock wells, and 21 bedrock wells were installed. These wells include monitoring wells, piezometers, well points, a collection well at OU4, and an injection well. One monitoring well was constructed of 4-inch diameter schedule 40 PVC. The remaining monitoring wells and piezometers were constructed of 2-inch and 1-inch diameter schedule 40 PVC, or for piezometers, 0.25 or 0.125 inch Teflon tubing. Well screens for monitoring wells and piezometers were installed with 0.010-inch factory-cut slots and mesh size 16-40 silica sand was used as filter pack. The intake section of well point piezometers consisted of small holes drilled into the tubing surrounded by a 16-40 mesh silica sand filter pack.

5.1.4.10 1994 Wells

During 1994 planned and currently installed wells include 15 piezometers at OU2, 15 piezometers at OU5, 8 wells at OU7, 13 wells at OU11, 19 wells under the WARP, and 15 piezometers in the dams under the Surface Water Program (T. P. Lovseth, personal communication, 1994).

5.1.5 Groundwater Monitoring Program Field Activities

5.1.5.1 Routine Sampling and Analysis

The groundwater sampling conditions at the Rocky Flats site are typified by low well yields controlled by the clayey character of water yielding deposits and limited saturated thickness; water level recovery rates ranging from minutes to over a year;

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moderate to deep water levels; a wide range of ambient annual air temperature extremes; relatively large sample volume requirements (approximately 4 gallons for a full sample suite); and stringent quality control, documentation, and reporting requirements. These conditions substantially impact the operational aspects of the Groundwater Monitoring Program and, in some cases, limit the type and amount of information that can be collected from a well. For example, of the 350 wells sampled in the 4th quarter of 1994, only 164 wells provided full sample suites after a two day sampling period. Of the remaining wells, 128 yielded partial sample suites and 58 wells were dry. These constraints, combined with the large number of wells and individualized program monitoring requirements, result in an comprehensive monitoring program that has exceptional and sometimes unique logistical, technical and administrative demands. In 1994 alone, the Groundwater Monitoring Program sampled a total of 1458 wells; measured a total of 5384 water levels; redeveloped 11 existing wells; and developed 25 new wells.

The operational groundwater sampling network consisted of 560 wells at the end of 4th quarter 1994. All wells containing sufficient water are sampled quarterly or semi-annually as specified by regulatory program compliance requirements and guidance, and other sources, such as approved RCRA and CERCLA remedial investigation work plans. Quarterly monitoring is performed for all RCRA wells in accordance with regulatory requirements. Quarterly monitoring is also performed at new, non-compliance monitoring wells for purposes of characterization until at least eight quarters of data are collected for representation of seasonal groundwater quality and verification of data accuracy. Starting in 1995, selected RCRA and CERCLA characterization wells will be sampled semi-annually rather than quarterly based on consideration of characterization objectives, historical water quality trends and the slow rate of migration observed for many existing contaminant releases.

All wells are purged and sampled according to procedures detailed in Operating Procedure 5-21000 OPS-GW.6 Groundwater Sampling (EG&G, 1991d). During sample collection, field measurements of temperature, specific conductance, pH, turbidity, and purge volume are made and recorded in field log forms. The samples are analyzed for a wide variety of analytes as shown in Table 5-2. Due to the limited water availability in many wells, partial sample suites are commonly collected according to the priority schedule set forth in OPS-GW.6. Generally, priority is given to unstable constituents, such as volatile organic contaminants, and contaminants of concern based on process and previous sampling knowledge. If water is not detected in the well after eight consecutive quarters, it is considered for abandonment.

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5.1.5.2 Quarterly Measurement of Groundwater Elevations

As part of the Groundwater Monitoring Program, 560 wells are measured for water levels during the first 10 days of each quarter. These data allow for preparation of the Rocky Flats site sitewide and OU-specific potentiometric maps, assist with quarterly sample planning and permit calibration of groundwater flow models, among other uses. All water levels are measured as described in Operating Procedure 5-21000 OPS-GW.1, Water Level Measurements in Wells and Piezometers (EG&G, 1991d). In addition, the well condition is assessed during this task and the information is used to coordinate subsequent monitoring tasks. Data has been collected in this manner since the first quarter of calendar year 1990.

Water level measurements collected prior to the first quarter of 1990 did not serve as a specific water-level measurement task. Groundwater levels were collected prior to purging during each sampling event but a complete set of water levels was not collected in a given time period.

5.1.5.3 Monthly Measurement of Groundwater Elevations

In addition to quarterly water-level measurements, a subset of the 560 monitored on a quarterly basis are measured for monthly water levels. These measurements are made to generate well hydrographs which allow for a better understanding of seasonal and long term water level fluctuations at the Rocky Flats site. This activity addresses both a regulatory requirement and a technical need to know groundwater flow directions and fluctuations. Measurements in wells which do not reflect equilibrium conditions based on comparisons to previous readings are flagged with an appropriate qualifier.

5.1.5.4 Well Maintenance

Well maintenance is an important aspect of the Groundwater Monitoring Program. Wells must be maintained to ensure the usefulness of the well to allow the collection of samples representative of groundwater quality. Well maintenance activities include routine assessment of sediment built-up in well sumps, sediment removal and redevelopment, well pad repair, and an overall assessment of well condition. Methods describing well maintenance activities are located in Operating Procedures 5-21000 OPS-GW.6, Groundwater Sampling and OPS-GW.2, Well Development (EG&G, 1991d).

5.1.6 Well Abandonment and Replacement

The Rocky Flats site has initiated a Well Abandonment and Replacement Program (WARP) to achieve the general objective of ensuring that groundwater monitoring wells and piezometers are capable of providing accurate and defensible groundwater

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samples and water level measurements that are representative of subsurface hydrologic conditions. Well abandonments and replacements are a part of general well maintenance activities for the Groundwater Monitoring Program. These maintenance activities provide a vehicle to maintain regulatory compliance with the Resource Conservation and Recovery Act (RCRA) 40 CFR 265.91 (c), monitoring well construction standards. The implementation of WARP also serves to maintain compliance with DOE Order 5400.1.

Wells that fail to meet criteria for viability and/or usefulness are abandoned using procedures that protect groundwater from surface contamination and cross-contamination between water-bearing zones. Most shallow monitoring wells are abandoned by removing or destroying the casing, drilling out the annular material, grouting the borehole and constructing a surface seal. When the casing cannot be removed to total depth, the wells are abandoned in place by setting a grout plug isolating the water table aquifer from the bedrock water-bearing units. Abandoned wells that are critical to the Groundwater Monitoring Program are replaced.

Since the beginning of 1992, the WARP has abandoned 121 groundwater monitoring wells and installed 34 groundwater monitoring wells. The follow summary outlines the program's history by year:

1989 Audit findings by the DOE Special Assignment Team of July 21, 1989 concluded that because wells of unknown construction have been installed at Rocky Flats, groundwater samples from these wells may not be representative of subsurface conditions. The audit also made the recommendation to initiate a well maintenance program and to abandon all wells with incomplete construction records.

1991 The Operating Procedures for the abandonment of groundwater monitoring wells were developed. GT.11, "Plugging and Abandonment of Wells," and GT.05, "Plugging and Abandonment of Boreholes" (EG&G, 1991e) were approved for use.

1992 Forty-six groundwater monitoring wells were abandoned and seven replacement wells were installed (1992 Well Abandonment and Replacement Program Final Report).

1993 Thirty-four groundwater monitoring wells were abandoned and eight replacement wells were installed. Three risers were installed on monitoring wells located in the landfill to extend the length of casing to accommodate the addition of fill material around the wells (1993 Well Abandonment and Replacement Program Final Report).

1994 Forty-one groundwater monitoring wells were abandoned and 19 wells were installed. Three risers were installed and three geotechnical borings were

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drilled. Twenty-eight monitoring wells were geophysically logged including surveys down-hole with a video camera (1994 Well Abandonment and Replacement Program Final Report).

5.1.7 Operating Procedures

The GMP operates under the control of a number of documents that outline programmatic and field operating procedures to ensure representative sample and data collection. The Groundwater Protection and Monitoring Program Plan (EG&G, 1993h) provides a comprehensive framework for GMP objectives and activities conducted under CERCLA. Operating Procedures, such as those referenced earlier in Section 5.1.5, control data collection activities and are CDH and EPA approved. Compliance with the requirements set forth in these documents produce data that are documentable, representative of actual groundwater conditions and reproducible. The reader is referred to the GPMPP for further discussion of GMP operating procedures and related topics, including quality assurance/quality control, data quality objectives and other data analyses.

5.1.8 Data Storage and Retrieval

Groundwater data collected by the GMP is ultimately stored in the Rocky Flats Environmental Database System (RFEDS). This system is a relational database developed to serve as a controlled source of analytical and field data. Data currently managed in RFEDS includes radiochemistry, volatile and semivolatile organic compounds, PCBs and pesticides, metals, and inorganic parameters for groundwater, surface water, boreholes, soils, and sediment monitoring samples. Field parameter data (i.e., sample location, sample date, pH, Eh, conductivity, and temperature) are included as well as groundwater level measurements, and chemical information (i.e., CAS numbers, physical parameters, detection limits). Each sample record in RFEDS contains a field for the validation code and four fields to qualify acceptable or rejected data. Specific procedures for verification of database information received from subcontractors or input directly into RFEDS have been developed and are being implemented. These procedures provide quality assurance/quality control (QA/QC) documentation that assures all available data have been incorporated and entered or uploaded properly into RFEDS. RFEDS data undergoes data verification prior to incorporation in the system. Other procedures are being developed for database system security and software change control.

All laboratory work is done to Contract Laboratory Program (CLP) standards except for radionuclides. The QA/QC for any non-CLP and non-radiochemistry also parallels CLP protocol to include continuous equipment calibrations and method blanks for every 1 in 10 samples. The CLP-type analysis is outlined in Section 2.4 of the General Radiochemistry and Routine Analytical Service Protocol (EG&G, 1990b). One

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hundred percent of all analytical data currently undergo an independent laboratory review for the validation process. This percentage will be reduced in the future to a statistically significant percentage, upon approval of the regulatory agencies.

5.2 Aquifer Testing Activities Conducted in 1994

Aquifer slug tests were conducted at 99 monitoring wells in 1994 in order to better define the lateral and vertical distribution of hydraulic conductivity at the site, and provide advance hydraulic conductivity estimates of the Rocky Flats alluvium from wells in the western Industrial Area. Testing was also conducted at several well sites with existing pumping test data to examine the possible correlation between slug test and pumping test-derived values. The results of testing and the slug/pump test correlation are presented later in Section 6.0. Table 5-3 lists the 99 wells tested during the 1994 aquifer testing program.

Slug tests were selected as the test method based on consideration of data objectives, cost, and in the case of bedrock wells, the hydrologic limitations imposed by low permeability materials. At least one test was performed at each well with many wells tested twice - first during slug insertion followed a second time during slug removal. Each test was analyzed using as many as three analysis methods (Bouwer and Rice; 1976; Hvorslev; and Ramey *et al.*, 1975) with consideration given to well and aquifer conditions, and the assumptions inherent to each method. The Ramey *et al.* (1975) slug test method was chosen over the more familiar Cooper *et al.* (1967) method because it estimates the hydraulic conductivity of undisturbed material by accounting for near-bore hole formation disturbances ("skin effect") created during drilling and subsequent well development activities. A more detailed description of the field test and analysis methodologies used for this project are given in EG&G (1994c), with complete documentation for each test provided in a companion set of appendices.

As presented in Appendix H, the most representative hydraulic conductivity value calculated for each well is indicated by a recommendation designation based on the judgment of the analyst. This designation was generally assigned to the most conservative value or, in some cases, average of values from the test and analysis method combination considered by the analyst to be the most representative of aquifer conditions. All results fall within the expected range of values of geologic materials encountered at the Rocky Flats site.

5.3 Groundwater Recharge (Rocky Flats Alluvium)

In 1993, a groundwater recharge monitoring project was initiated to provide quantitative information on annual groundwater recharge to the Rocky Flats alluvium for groundwater modeling applications. The project consisted of a field and laboratory investigation of soil properties conducted at two sites in the east trenches area of

Operable Unit 2, followed by routine monitoring of the soil moisture profile using tensiometers and neutron access tubes. These sites were selected based on their proximity to several OU2 individual hazardous substance sites; consideration of field operations requirements, such as minimizing the production of potentially contaminated investigation-derived soil materials; and a combination of favorable hydrologic conditions, including a well characterized hydrogeologic setting and relatively shallow depth to water and bedrock.

Six bore holes were drilled at each of the two sites to bedrock using a solid-stem auger to depths of 8 to 10 feet at Site 1, and 31 to 32 feet at Site 2. A standard 140-pound drive sampling system was used to obtain a continuous length of "undisturbed" core contained in brass liners. Samples were visually inspected to choose specific segments for geotechnical analyses. Criteria for selection of samples for analysis included amount of recovery, lack of void space within the liner, and grain size. Twenty-six soil samples were submitted to two different geotechnical laboratories for determination of physical properties. Sampled intervals were chosen to correspond as closely as possible to neutron meter count locations. Tests, including moisture content, specific gravity, grain-size distribution, unsaturated hydraulic conductivity/moisture characteristic curves, and diffusivity (Bruce-Klute) were determined from bore hole samples.

Aluminum casing was installed along the lengths of two bore holes and PVC casing was installed along the lengths of the other ten bore holes. Ideally, aluminum casing would have been used in all bore holes because it is stronger than PVC and does not interfere with neutron measurements. However, availability and cost of aluminum casing prevented its widespread use. The casing provides access for down-hole neutron moisture meter measurements used to develop soil-moisture profiles at each of the sites.

To date, the results of the groundwater recharge project are primarily limited to laboratory measurements. A limited amount of field data has been collected, mainly involving a preliminary sprinkler experiment conducted in September 1993. Field measurements were temporarily suspended in fiscal year 1994 to resolve various contract, work plan and health and safety plan issues, and were later resumed in November 1994. The available field and laboratory results are contained within EG&G (1993e).

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Table 5-1
Wells and Piezometers Installed by Year

Year	Total Wells and Piezometers	Active Wells	Active Piezometers
Pre-1986	100	0	14
1986	71	49	11
1987	67	45	15
1988	10	0	0
1989	163	79	65
1990	17	4	4
1991	143	99	32
1992	49	38	0
1993	152	40	25
1994[1]	41	28	13
Total	**780**	**382**	**179**

[1] As of 3rd quarter 1994. No wells were installed during the first two quarters of 1994.

Table 5-2
Chemical Constituents Monitored in Groundwater During 1994

Field Parameters
pH
Specific Conductance
Temperature
Dissolved Oxygen
Alkalinity
Indicators
Total Dissolved Solids (TDS)
Total Suspended Solids (TSS)
pH[1]
Metals
Target Analyte List:
Aluminum (Al)
Antimony (Sb)
Arsenic (As)
Barium (Ba)
Beryllium (Be)
Cadmium (Cd)
Calcium (Ca)
Chromium (Cr)[2]
Cobalt (Co)
Copper (Cu)
Iron (Fe)
Lead (Pb)
Magnesium (Mg)
Manganese (Mn)
Mercury (Hg)
Nickel (Ni)
Potassium (K)
Selenium (Se)

Table 5-2
Chemical Constituents Monitored in Groundwater During 1994

Silver (Ag)
Sodium (Na)
Thallium (Tl)
Vanadium (V)
Zinc (Zn)
Others
Cesium (Cs)
Lithium (Li)[3]
Molybdenum (Mo)
Strontium (Sr)
Tin (Sn)[1]
Anions
Carbonate (CO_3)
Bicarbonate (HCO_3)
Chloride (Cl)
Fluoride (F)
Sulfate (SO_4)
Nitrate/Nitrite (NO_2/NO_3)
Cyanide (as N)[4]
Volatile Organic Compounds[5]
Target Compound List - Volatiles:
Chloromethane (CH_3CL)
Bromomethane (CH_3Br)
Vinyl Chloride (C_2H_3CL)
Chloroethane (C_2H_5Cl)
Methylene Chloride (CH_2CL_2)
Acetone
Carbon Disulfide
1,1-Dichloroethane (1,1-DCA)
1,1,-Dichloroethene (1,1-DCE)
trans-1,2-Dichloroethene
1,2-Dichloroethene (total) (total 1,2-DCE)

Table 5-2
Chemical Constituents Monitored in Groundwater During 1994

Chloroform ($CHCl_3$)
1,2-Dichloroethane (1,2-DCA)
2-Butanone (MEK)
1,1,1-Trichloroethane (1,1,1-TCA)
Carbon Tetrachloride (CCL_4)
Vinyl Acetate
Bromodichloromethane
1,1,2,2-Tetrachloroethane
1,2-Dichloropropane (1,2-DCP)
trans-1,3-Dichloropropene
Trichloroethylene (TCE)
Dibromochloromethane
1,1,2-Trichloroethane
Benzene
cis-1,3-Dichloropropene
Bromoform(CBr_4)
2-Hexanone
4-Methyl-2-pentanone
Tetrachloroethene (PCE)
Toluene (C_7H_8)
Chlorobenzene (C_6H_5CL)
Ethyl Benzene
Styrene
Xylenes (Total)
Radionuclides[6]
Gross Alpha - dissolved
Gross Beta - dissolved
Uranium 233/234; 235 - total; and Uranium 233, 234, 235 and 238 - dissolved
Americium 241 (Am-241) - total
Plutonium 239+240 (Pu-239,240) - total
Strontium 89+90[7] (Sr-89,90)[8] - dissolved
Cesium 137 (Cs-137) - dissolved

Table 5-2
Chemical Constituents Monitored in Groundwater During 1994

Tritium
Radium 226; 228 (Ra-226,228) - dissolved

1. Not analyzed prior to 1989.
2. Analyses in 1990 are for total chromium. Chromium (IV) was analyzed during fourth quarter 1987 only.
3. Prior to 1989, lithium was only analyzed during fourth quarter 1987 and first quarter 1988.
4. Cyanide was not analyzed during fourth quarter 1987.
5. Not analyzed in background samples in 1989.
6. Dissolved radionuclides replaced total radionuclides (except tritium) beginning with the third quarter 1987. During 1991 and 1992, total concentrations of Am-241, Pu-239,240, and tritium were analyzed.
7. Strontium 89+90 was not analyzed during first quarter 1988.
8. Not analyzed prior to 1989 and only analyzed if gross alpha exceeds 5 pCi/L.

Table 5-3
Aquifer Slug Tests Conducted in 1994 by Well Number

3086	B203489	P414189	P416589	03391
3886	B203589	P114389	P416689	11791
4086	B203789	P114489	P416789	11891
4486	B203889	P114689	P416889	13491
4686	B203989	P114789	P416989	20291
4886	B204089	P114889	B217489	20491
6186	B204189	P114989	B217589	20591
6686	B304889	P115089	B217689	20691
1687	B304989	B315289	B217789	20791
1887	B405289	P115489	P317989	20891
2087	B305289	P115589	P218089	20991
2287	B405689	P115689	P119389	46392
2387	B405789	P215789	P419689	46492
2587	B206589	P415889	P320089	46692
2887	B206789	P415989	0590	46792
3187	P207989	P416089	0690	46892
3487	P313489	P416189	0790	00293
3687	P313589	P416289	0990	23193
B203189	P213689	P416389	00491	70593
B203289	P314089	P416489	01991	

6. Hydrogeology of the Rocky Flats Site

This section discusses the hydrogeology of the Rocky Flats site and includes a discussion of the hydrostratigraphic unit concept as currently applied at the site, surface-water/groundwater interactions, and the occurrence and flow of groundwater in each sub-unit composing the upper hydrostratigraphic unit (UHSU) and lower hydrostratigraphic unit (LHSU). Specific examples of important hydrogeologic features, such as hillside colluvial hydrology and bedrock controls of UHSU groundwater flow, are also provided.

6.1 Definition of Hydrostratigraphic Units

The interpretation of and the terminology used to describe the hydrogeologic setting at the Rocky Flats site has evolved with the accumulation of data. The terminology used is intended to conform with RCRA and CERCLA regulations. Early hydrogeologic characterization of the Rocky Flats site in the Final Environmental Impact Statement recognized and described separate groundwater flow systems within the Rocky Flats Alluvium, the Arapahoe Formation, and the Laramie/Fox Hills Formation (ERDA, 1980). Later hydrogeologic summaries described shallow and deep groundwater flow systems at Rocky Flats. The shallow system included groundwater within the Rocky Flats Alluvium, colluvium, and valley-fill alluvium, and the deep system included groundwater within the claystones and sandstones of the Arapahoe Formation (Hydro-Search Inc., 1986; Rockwell International, 1986b). The most current interpretation used to describe the hydrologic setting is the UHSU/LHSU distinction. This definition is supported by hydraulic data and geochemical and isotopic studies reported in the Groundwater Geochemistry Report (EG&G, 1995b).

6.1.1 Hydrostratigraphy as Defined by Regulatory Guidance

RCRA legislation required the implementation of a groundwater monitoring program that was "capable of determining the facilities impact on the quality of groundwater in the uppermost aquifer underlying the facility." This necessitated the interpretation of the "uppermost aquifer" for groundwater monitoring and compliance at RCRA-regulated units. The uppermost aquifer "means the geologic formation nearest the natural ground surface that is an aquifer, as well as lower aquifers that are hydraulically interconnected with this aquifer within the facilities boundary" (40 CFR 264, Subpart F).

The term "aquifer" is defined in 40 CFR 191.12(I), Subpart B, as any geologic formation, group of formations, or portion of a formation capable of yielding significant and useable quantities of groundwater to wells or springs. This may include

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fill material that is saturated. CERCLA guidance defines aquifer in a similar manner but includes any geologic material that is currently used or could be used as a source of water. Identification of formations capable of "significant yield" must be made on a case-by-case basis (EPA, 1986). Monitoring of the uppermost aquifer is required under 40 CFR 264, Subpart F, in order to immediately detect contaminant releases. The identification of the confining layer or lower boundary is an essential facet of the definition of the uppermost aquifer (EPA, 1986). The confining unit or lower boundary must be proven to be of low enough permeability to minimize the passage of contaminants to lower saturated units. Determination of the hydraulic connection between stratigraphic units should be based on multiple well pump tests. If drawdown in a well in one unit is reflected in wells from the other unit, the lower boundary should not be considered of low enough permeability to significantly retard contaminant migration between the units. Wells within a hydrostratigraphic unit should display similar patterns of drawdown and response to seasonal recharge and discharge events.

If zones of saturation capable of yielding significant amounts of water are interconnected (based on information from pump tests), they all compose the uppermost aquifer. Quality and use of groundwater are not factors in the definition of the uppermost aquifer. Even though a saturated formation may not be in use currently or contain water not suitable for human consumption, it may deserve protection because contamination may threaten human health or the environment (EPA, 1986).

Saturated zones that are not capable of yielding significant amounts of water, such as low-permeability clays, may act as pathways for contaminant transport (EPA, 1986). Migration of contaminants along these pathways may result in contamination of zones capable of yielding significant amounts of water. Monitoring of these zones of low permeability may be required under RCRA, 42 USC 6928, interim status corrective action section 3008(h) and corrective action for permitting section 3004(u). However, if contaminants have been detected in a unit, the plume should be characterized regardless of the groundwater yield of the unit (EPA, 1986).

Based on the regulatory, as well as technical, definitions of an aquifer, annual RCRA reports for regulated units at Rocky Flats have determined that the upper groundwater flow system at the Rocky Flats site is not an aquifer because the yield of water to wells is typically low and broad areas of the system are unsaturated during the fall and early winter. Given these conditions it is unlikely that the upper flow system could yield significant amounts of water; however, it has been described as water bearing (DOE, 1989). Although the upper flow system at Rocky Flats is not considered to be an aquifer, the RCRA definitions have been applied for the development of a practical groundwater monitoring system that complies with the intent of the 40 CFR 264, Subpart F, groundwater protection regulations and ensures the protection of public health and the environment.

Annual RCRA reports for regulated units at Rocky Flats for 1986, 1988, 1991, and 1992 described the Rocky Flats Alluvium, colluvium, and valley-fill alluvium to best fit the RCRA definition of the uppermost aquifer based on their proximity to the ground surface and their relatively high hydraulic conductivities. The units also are connected hydraulically as indicated by the well hydrographs discussed in Section 6.2.3. There is considerable interflow between these units, and discharge from one unit may recharge other units. Discharge from the Rocky Flats Alluvium recharges hillside colluvium, and discharge from hillside colluvium recharges valley-fill colluvium (see Section 6.2.3 for a more complete discussion).

It also was recognized that in certain areas the hydraulic conductivities of some weathered sandstones and claystones within the Arapahoe and Laramie formations were similar to those in the unconsolidated surficial materials. These units also appear to be connected hydraulically with the surficial deposits based on analysis of hydrographs (see Section 6.2.3). Discharge from surficial deposits generally recharges weathered bedrock; however, this relationship is reversed in some cases. The hydraulic connection between some sandstones and weathered bedrock and surficial deposits indicates that they should be considered as part of the same hydrostratigraphic unit because of the absence of a low-permeability layer capable of minimizing flow between these units. Therefore, the sandstones and weathered claystone were considered part of the "uppermost aquifer" where they subcropped beneath saturated surficial material that had been contaminated by a RCRA regulated unit (Rockwell International, 1986b and 1988; EG&G, 1992c, 1993f, and 1994b). For a complete discussion of interaction between surficial deposits and weathered bedrock, see Section 6.2.3.

Unweathered bedrock of the Arapahoe and Laramie formations represents a significant contrast in permeability to the weathered bedrock and surficial deposits. In general, wells completed in unweathered bedrock do not display direct hydraulic connection to overlying surficial deposits and weathered bedrock, as indicated by well-cluster hydrographs. However, local groundwater interaction between weathered and unweathered bedrock is evident at some locations (see Section 6.4). In general, the low hydraulic conductivity of the unweathered bedrock acts as an effective barrier to downward groundwater flow. Unweathered bedrock of the Arapahoe and Laramie formations is not considered part of the UHSU due to its contrast in permeability and lack of hydraulic connection with the overlying weathered bedrock and unconsolidated surficial deposits. The unweathered bedrock units are identified as a confining layer capable of minimizing vertical migration based on these characteristics.

6.1.2 Hydrostratigraphy at Other Front Range Superfund Sites

The concept of hydrostratigraphic units has been used to describe the hydrogeologic setting at the Rocky Mountain Arsenal. The two main water-bearing units at the Rocky

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Mountain Arsenal are the unconsolidated alluvial deposits and the underlying Denver Formation. The hydraulic properties of these two units, including hydraulic conductivity, are distinctly different, and the two units behave as two distinct hydrostratigraphic units. The alluvial deposits and the weathered portions of the Denver and Arapahoe formations are included in the upper hydrostratigraphic unit, and the lower hydrostratigraphic unit exists within the underlying Denver and Arapahoe formations. The alluvial material at Chemical Sales, Sand Creek Industrial, Woodbury Chemical, and Broderick Wood Products Superfund sites are hydrogeologically described as water-bearing units or as aquifers and are not characterized as and incorporated into hydrostratigraphic units (EG&G, 1995b).

6.1.3 Hydrostratigraphy at the Rocky Flats Site

The 1991 Geologic Characterization Report (EG&G, 1991b) used the concept of hydrostratigraphic units rather than aquifers to describe the hydrogeologic setting at the Rocky Flats site. Fetter (1988) defines hydrostratigraphic unit as a formation, part of a formation, or group of formations in which there are similar hydrologic characteristics allowing for grouping into aquifers or confining layers. Hydrostratigraphic units comprise geologic units grouped together on the basis of similar hydraulic properties. Several geologic formations may be grouped into a single aquifer, or a single geologic formation may be divided into both aquifers and confining units. The geologic characterization performed in 1991 considered the uppermost hydrostratigraphic unit at Rocky Flats to consist of alluvial material and subcropping sandstones.

The 1993 Annual RCRA Report was the first RCRA report to employ the concept of upper and lower hydrostratigraphic units at the Rocky Flats site to describe and identify the "uppermost aquifer." The report describes the UHSU as comprising several distinct lithostratigraphic units: Quaternary alluvium, colluvium, valley-fill alluvium, weathered bedrock of the Arapahoe and Laramie formations, and all sandstones within the Arapahoe and Laramie formations that are in hydraulic connection with overlying unconsolidated surficial deposits or the ground surface. They describe the LHSU as comprising unweathered bedrock of the Arapahoe and Laramie formations. The base of weathering in bedrock was used as the marker separating the upper and lower hydrostratigraphic units. This hydrostratigraphic unit designation was based on hydrologic and geochemical data that demonstrated hydraulic connection between the distinct lithostratigraphic units above the base of weathering in bedrock and a general hydraulic separation between unweathered bedrock and overlying units (EG&G, 1994b). Hydrologic, geologic, and geochemical data collected for the sitewide geoscience characterization reports were used to further evaluate the upper and lower hydrostratigraphic unit concept and the legitimacy of using the base of weathering in bedrock as the distinction between the UHSU and LHSU.

Hydraulic conductivity data can be used in a relative sense to evaluate the potential for hydraulic connection between various lithologic units. Hydraulic connection between unconsolidated surficial deposits and the underlying weathered bedrock at Rocky Flats is indicated by their similar hydraulic conductivities. Weathered bedrock sandstones and siltstones have geometric mean hydraulic conductivities of 3.89E-05 cm/sec and 2.88E-05 cm/sec, respectively. The geometric mean hydraulic conductivity of the weathered Arapahoe Formation sandstone is 7.88E-04 cm/sec. The Rocky Flats Alluvium, valley-fill alluvium, and colluvium have geometric mean hydraulic conductivities of 2.06E-04, 2.16E-03, and 1.15E-04, respectively. Mean hydraulic conductivities of weathered bedrock sandstones and siltstones are equal to or within one order of magnitude of unconsolidated surficial deposit hydraulic conductivities. This suggests the potential for hydraulic connection between weathered bedrock sandstones and siltstones and the overlying unconsolidated surficial deposits. The mean hydraulic conductivity of weathered bedrock claystone is 8.82E-07 cm/sec which is more comparable to the hydraulic conductivities of unweathered bedrock lithologies than to unconsolidated surficial deposits. Unweathered bedrock sandstone, siltstone, and claystone mean hydraulic conductivities are 5.77E-07, 1.59E-07, and 2.48E-07, respectively. The relatively low hydraulic conductivity of the unweathered bedrock suggests that it acts as a barrier to downward groundwater flow and that it effectively minimizes groundwater interaction between units above and below the base of weathering. This is supported by hydrograph data that indicate unweathered bedrock and UHSU deposits are not hydraulically connected.

Characteristics of groundwater flow within and among the various lithostratigraphic units that comprise the UHSU must be similar in order for the present upper and lower hydrostratigraphic unit concept at the Rocky Flats site to be used effectively in evaluating potential contaminant migration. Reports have shown that the potentiometric surface within the weathered bedrock is similar to that within the unconsolidated deposits. Thus, groundwater flow patterns within the weathered bedrock are expected generally to parallel those observed in the unconsolidated deposits. Figure 6-1 illustrates the hydrostratigraphy at Rocky Flats using an example from OU2 (DOE, 1991). The schematic cross section depicts several important groundwater flow characteristics related to the UHSU and LHSU classification at the Rocky Flats site. These include direct hydraulic connection between the lithostratigraphic units that compose the UHSU, which results in groundwater flowpaths that pass between different lithostratigraphic units within the UHSU. The contrast in hydraulic properties between the UHSU and LHSU results in predominately lateral groundwater flow at the UHSU/LHSU boundary.

Similar seasonal groundwater-level fluctuations occur in unconsolidated surficial deposit and weathered-bedrock wells. Although seasonal groundwater-level fluctuations do not occur at all unconsolidated deposit or weathered-bedrock wells, the

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temporal nature of the fluctuations are comparable. High groundwater levels in both the unconsolidated deposits and the weathered bedrock occur in the spring, and low groundwater levels occur in late summer and fall. These groundwater fluctuations indicate that the unconsolidated surficial deposits and the weathered bedrock respond similarly to seasonal recharge events. Although this response is not universal, it does indicate local hydraulic connection between the unconsolidated surficial deposits and weathered bedrock. This is discussed in more detail in Section 6.3.2.

Well clusters that are screened in unconsolidated deposits and weathered bedrock reveal that the dominant vertical hydraulic gradient is downward. Some clusters indicate a complete hydraulic connection between the unconsolidated deposits and the weathered bedrock because their potentiometric surfaces are essentially equal. Other clusters identify areas in which groundwater within the unconsolidated surficial deposits is perched on top of less permeable weathered bedrock and the upper portion of the weathered bedrock is unsaturated. Downward vertical hydraulic gradients within these areas suggest vertical groundwater flow from unconsolidated deposits into the weathered bedrock. Subcropping weathered sandstones and siltstones have similar hydraulic conductivities as the overlying unconsolidated deposits, enhancing the amount of interaction between the units. Bedrock structural features such as faults and slumps may also enhance groundwater interaction between weathered bedrock and the unconsolidated surficial deposits. For a complete discussion on unconsolidated surficial deposit/weathered-bedrock groundwater interactions, refer to Section 6.2.3.

Well clusters screened in units above and below the base of weathering in bedrock generally indicate minimal hydraulic connection between weathered and unweathered bedrock. However, some well clusters in weathered/unweathered bedrock show similar groundwater-level responses above and below the base of weathering in bedrock. The specific interactions are discussed in Section 6.4.1.1. Similar groundwater fluctuations in well clusters screened at relatively shallow depths within the unweathered bedrock and UHSU wells may indicate localized areas of hydraulic connection between weathered and unweathered bedrock. However, the relatively low hydraulic conductivity of the unweathered bedrock and the general lack of correlation in water-level responses between LHSU and UHSU wells suggests that the unweathered bedrock generally acts as an effective barrier to downward groundwater flow. For a complete discussion on UHSU and LHSU interactions, refer to Section 6.4.

Groundwaters collected from unconsolidated surficial deposits and from weathered bedrock are not typically distinguishable from one another on the basis of their major-ion compositions. The Rocky Flats Alluvium, colluvium, valley-fill alluvium, and weathered bedrock all contain predominantly calcium-bicarbonate-type groundwater (EG&G, 1993b and 1994e). The similarity in the composition of groundwater from

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these units suggests that the units receive recharge from the same source and that they are hydraulically connected to one another.

In contrast, groundwater from unweathered bedrock is much more variable in its chemical composition, and it typically has a different major-ion composition than groundwater from the other lithostratigraphic units at Rocky Flats. In general, groundwater from unweathered bedrock is more sodium-rich than groundwater from the other units and it has a sodium-bicarbonate to sodium-sulfate composition (EG&G, 1995b).

Groundwaters from the various lithostratigraphic units are not generally distinguishable from one another on the basis of $\delta^{18}O$ and δD values. There is a shift to slightly higher $\delta^{18}O$ and δD values with increasing depth in unweathered bedrock. However, no clear break in groundwater types is indicated by $\delta^{18}O$ and δD data (EG&G, 1995b).

A general contrast in groundwater tritium contents exists between lithostratigraphic units above and below the base of weathering in bedrock. Tritium contents in groundwater within the weathered bedrock and unconsolidated surficial deposits typically range from 10 to 50 tritium units (TU). There is generally no measurable tritium in groundwater within the unweathered bedrock. The contrast in tritium contents from above and below the base of weathering in bedrock appears related to distinct sources of recharge but may also reflect large differences in the age of groundwater above and below the base of weathering in bedrock. Non-detectable amounts of tritium indicate that the main component of groundwater in the unweathered bedrock is more than 40 years old. Tritium concentrations in groundwater from weathered bedrock and the overlying unconsolidated deposits are consistent with groundwater ages of less than 40 years, indicating that recharge to these units is more recent. The relatively sharp break in the vertical profile of groundwater tritium contents at the base of weathering in bedrock may be the result of the low permeability of the unweathered bedrock. However, despite the break in tritium contents, there is evidence for some mixing between units above and below the base of weathering in bedrock. Detectable concentrations of volatile organic compounds (VOCs) in unweathered bedrock groundwater indicate relatively recent recharge from the upper units (EG&G, 1995b).

Hydraulic data from well clusters and groundwater geochemical data provide a basis for defining separate hydrostratigraphic units above and below the base of weathering in bedrock. The inclusion of weathered bedrock into the UHSU is also generally supported by hydraulic and geochemical data. On a sitewide scale, the relatively low hydraulic conductivity of unweathered bedrock distinguishes it hydraulically from the overlying units, although some data indicate localized areas of hydraulic connection between lithostratigraphic units above and below the base of weathering in bedrock.

6.2 Upper Hydrostratigraphic Unit

The UHSU at Rocky Flats consists of unconsolidated surficial deposits, weathered bedrock, and sandstones in hydraulic connection with overlying units.

6.2.1 Surficial Deposits

This description of the hydrogeology of unconsolidated surficial deposits focuses on the Rocky Flats Alluvium, colluvium, landslide deposits, and valley-fill alluvium. These units represent the bulk of the surficial deposits that are present at the Rocky Flats site. Other alluvial deposits such as the Verdos Alluvium, Slocum Alluvium, and undifferentiated terrace alluvium are present in relatively minor quantities and do not represent a significant component of the hydrogeologic system at the Rocky Flats site.

Included in this section are the following discussions: a summary of surficial deposits geology; the occurrence and distribution of groundwater; descriptions of recharge and discharge; a summary of the hydraulic properties of the surficial deposits; and presentation of the flow conditions present in the surficial deposits, including specific examples from various locations at the Rocky Flats site.

6.2.1.1 Geology of the Surficial Deposits

This section summarizes the surficial deposits geology as presented in the Geologic Characterization Report (EG&G, 1995a). For a more detailed discussion of the surficial geology, please refer to Section 4 of the Geologic Characterization Report.

Surficial deposits at the Rocky Flats site consist of Quaternary-age units that unconformably overlie the Arapahoe and Laramie formations. The Industrial Area is located on a pediment capped by Rocky Flats Alluvium, which is the oldest and topographically highest of the surficial deposits in the area. This pediment has been eroded by streams that have cut steep valleys into the Rocky Flats Alluvium and underlying bedrock. As a result, reworked Rocky Flats Alluvium and bedrock have been deposited as colluvium on the valley slopes. The continued undercutting of the valley slopes by streams has also caused landslides to occur along the margins of the Rocky Flats Alluvium. In the bottom of the incised valleys, deposits of valley-fill alluvium represent the most recent episode of deposition in the Rocky Flats area. Plate 2-1 (EG&G, 1995a) provides a map of the surficial deposits showing the topographic and lateral relationships of the units.

Rocky Flats Alluvium is composed of a series of coalescing alluvial fans deposited during the Pleistocene. The Rocky Flats Alluvium is thickest near the mouth of Coal Creek Canyon and thins to the east at the depositional limits of the fan. At the Rocky Flats site, the Rocky Flats Alluvium ranges in thickness from less than 5 to more than

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100 feet (EG&G, 1995a). The Rocky Flats Alluvium generally consists of unconsolidated, well-graded coarse gravels, coarse sands, and gravelly clays. Discontinuous lenses of clay, silt, and sand are also common within the unit indicating the heterogeneous nature of Rocky Flats Alluvium (EG&G, 1994a).

Holocene-age colluvium is typically present on valley slopes and is composed of reworked Rocky Flats Alluvium and bedrock materials. Sheet erosion and gravity creep processes formed the colluvial sequences, which vary in thickness from 3 to 15 feet (EG&G, 1995a). The thickest deposits occur at the base of valley slopes. Colluvial deposits are composed of clay, clayey gravel, and gravelly clay with smaller amounts of sand and silt. The clay and silt content of the colluvial deposits derived from the Arapahoe and Laramie formations is relatively higher than that of the colluvium derived from Rocky Flats Alluvium (EG&G, 1994a).

Landslide and slump deposits at the Rocky Flats site were formed by a variety of mass movement processes involving the downslope transport of unconsolidated material and rock *en masse*. Landslide and slump deposits are most common on valley slopes and vary in thickness from 10 to 50 feet. Unsorted and unstratified unconsolidated material and rock fragments of varying sizes are characteristic of the landslide deposits. Earth flows, earth slump, debris flows, debris slumps, rock-block slides, and complex landslides are landslide types that have been identified in the Rocky Flats area (Varnes, 1978). In some cases, landslides may consist of large debris flows containing primarily surficial deposits, and other landslide deposits are a combination of both surficial deposits and large rotated blocks of bedrock.

For purposes of this discussion of sitewide hydrogeology, the landslide deposits are grouped together with colluvial deposits. This assumption is valid for a discussion of the hydrogeology of the surficial deposits for the following reasons:

- The physical and hydraulic properties of the two units are expected to be largely the same because they are composed of the same material.
- The same processes are generally responsible for deposition of both landslide material and colluvium.
- A primary difference in landslide and colluvial deposits is the scale of slumping and mass wasting.
- Landslide and colluvial deposits occur in similar areas.

Valley-fill alluvium consists of fluvial-alluvial deposits, which occur in and adjacent to the ephemeral streams present at the Rocky Flats site. The valley-fill alluvium, also referred to as the Piney Creek Alluvium, includes the Piney Creek Alluvium of Hunt

(1954) and the post-Piney Creek Alluvium of Malde (1955). These sediments are composed of clay, silt, sand, and pebbly sand with silty and cobbly gravel lenses. Valley-fill deposits range in thickness from 0 to greater than 40 feet, with an average thickness of 10 feet.

6.2.1.2 Groundwater Occurrence and Distribution

Groundwater within surficial deposits generally occurs under unconfined conditions. The occurrence and distribution of groundwater in this system are influenced by the following factors: surface topography, bedrock topography, seasonal variations in precipitation, thickness of the surficial deposits, the presence of engineered structures, and the presence of impermeable zones.

Potentiometric Surface

Potentiometric-surface maps of groundwater within the surficial deposits were constructed for spring and fall (second and fourth quarters) of 1993 (Plates 2 and 3). These maps indicate that groundwater flow is largely controlled by the topography of the bedrock surface. Generally, the configuration of the potentiometric surface resembles bedrock topography. Groundwater in the ridge tops generally flows toward the east-northeast. In areas where the ridge tops are dissected by the east-northeast-trending stream drainages, groundwater flows to the north or south toward the bottom of the valleys. In the valley bottoms, groundwater flows to the east, generally following the course of the stream.

Seasonal variations in precipitation are reflected in the potentiometric surface. The potentiometric surface is typically higher in the spring (second quarter) and lower in the winter (fourth quarter). Seasonal variations generally do not affect the sitewide flow directions. Areas of unsaturated surficial deposits, however, are larger in the fourth quarter when water levels are typically lowest. The variation in the extent of unsaturated areas is greatest in the eastern part of the site in OUs 1, 2, and 4. In the western part of the site, unsaturated areas are small or not present (Plates 2 and 3).

Saturated Thickness

The saturated thickness of the surficial deposits is generally greatest in the western part of the site and decreases across the Industrial Area and eastern portions of the site (Plates 4 and 5). Saturated thickness ranges from over 40 feet in the western Buffer Zone to less than 5 feet in the eastern half of the Industrial Area. Along the hillsides and stream valleys, the saturated thickness is typically less than 5 feet. In addition, there are unsaturated zones in many locations across the site particularly in the eastern half of the Industrial Area. The volume of water stored in the units beneath Rocky Flats was estimated in the Groundwater Protection and Monitoring Program Plan

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(EG&G, 1991c). This report estimates that the volume of water stored in the alluvium and valley-fill as 19,400 acre-feet (Table 6-1).

The size of unsaturated areas at the Rocky Flats site varies seasonally. For example, the unsaturated areas in OU2 are less extensive during the second quarter (Plate 4). During the spring when water levels are highest, additional areas of surficial deposits become saturated. The occurrence of these saturated and unsaturated areas in OU2 is controlled largely by bedrock topography. Surficial deposits overlying bedrock ridges are typically unsaturated, and deposits overlying bedrock valleys are more likely to be saturated (DOE, 1993b). In OU4, the bedrock surface affects the occurrence of unsaturated areas in a similar fashion. However, the large unsaturated area located north of the Solar Ponds and outside of the central portion of the Industrial Area is caused primarily by the Interceptor Trench System. This system removes groundwater from the surficial deposits by means of a series of French drains (DOE, 1994b).

Variations in surface and bedrock topography result in changes of the saturated thickness of surficial deposits. The surficial deposits isopach map (EG&G, 1995a, Plate 4-2) shows the net variation in the bedrock and topographic surfaces. In the western half of the site, thickness of surficial deposits ranges from 40 to 100 feet and saturated thickness ranges from 20 to 40 feet. Potential water storage in the surficial deposits is greater in this area because of the greater thicknesses of surficial deposits and because there are no stream valleys draining this area. In the central part of the site, the surficial deposits are thinner (5 to 30 feet), and saturated thicknesses also decrease (0 to 20 feet). Here, much of the groundwater flows from the ridge tops downward to the stream valleys or is discharged to the surface at contact seeps along the margins of the ridges. As a result, saturated thickness decreases due to discharges to the surface and stream valleys. Examples of contact seeps that represent discharge from colluvial/alluvial groundwater are the seeps south of Pond B-5 (DOE, 1993b) and some of the seeps north of the Solar Ponds (DOE, 1994c).

The decrease in saturated thickness may also be caused by impermeable areas in the Industrial Area. The impermeable areas greatly limit the infiltration and remove a source of recharge to surficial deposits in the Industrial Area. Approximately 190 of 438 acres within the Industrial Area are covered by impermeable areas.

Bedrock channels also locally affect the saturated thickness of surficial deposits. For example, a well-defined bedrock channel exists in OU2 near the southeastern perimeter (EG&G, 1995a, Plate 4-3) of the Industrial Area (EG&G, 1995a, Plate 4-3). The channel is approximately 25 feet deep; 300 feet wide; and 2,000 feet long. Surficial deposits in the bottom of this channel are perennially saturated; whereas the surficial deposits overlying the bedrock ridges adjacent to the channel are unsaturated (DOE, 1993b). Another bedrock channel trending north-south in the West Spray Field is also associated with an area of locally increased saturated thickness (Plates 4, 5, and 6). This channel is poorly delineated by existing well control. Bedrock channels in the OU4 area also affect the occurrence of unsaturated zones. However, the channels in OU4 are much shallower and narrower than those found in OU2. For example, one channel that affects the saturated thickness of the overlying surficial deposits measures approximately 30 feet wide by 5 feet deep (DOE, 1994c). However, due to the limited saturated thickness of surficial deposits in OU4, bedrock channels play an important role in the occurrence of saturated areas.

Engineered structures also cause variations in saturated thickness of the surficial deposits. In the southwestern part of the Rocky Flats site, geochemical data indicate that Rocky Flats Lake recharges surficial deposits and results in an increase in saturated thickness (EG&G, 1995b) (Plates 3 and 4).

Other examples of engineered structures that affect the saturated thickness of the surficial deposits include the Interceptor Trench System (ITS), located north of the Solar Evaporation Ponds, and the OU1 French drain. These systems locally remove groundwater from surficial deposits (DOE, 1992d and 1994f). The OU4 ITS collects approximately 3.1 million gallons of water per year along a 1,500-foot reach and removes groundwater from approximately 80 percent of the area it covers. As much as 36 percent of the water collected by the ITS may be stormwater runoff from the Building 779 area (DOE, 1994c). Engineered structures around the Present Landfill lower the water table as much as 15 feet in surficial deposits. However, a breach in the northern part of the Groundwater Intercept System has allowed groundwater inflow into the center of the landfill resulting in a locally greater thickness of saturated material (DOE, 1994a).

Depth to Water

Average depth to water across the Rocky Flats site varies from 0 to 70 feet (Plate 7). Depth to water is commonly used as an indicator of recharge and discharge areas. Recharge zones are often associated with areas of greater depth to water, whereas discharge areas are found where depth to water approaches zero. At the Rocky Flats site, depth to water is greatest in the western portions of the site indicating that this area is a recharge zone. Depth to water decreases across the Industrial Area to the east, in stream drainages, and at seeps, which are generally located along the extent of the Rocky Flats Alluvium.

In general, the depth to water appears to be controlled by the thickness of the surficial deposits, which is a function of the surface and bedrock topography. In areas of thickest alluvium such as the greater West Spray Field area, the northeast-trending ridge south of Rock Creek, the ridge south of the B-series ponds, and the area northeast

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of Rocky Flats Lake, depth to water is generally greater indicating that these areas of the pediment alluvium are recharge zones. Depth to water decreases in areas of thinner surficial deposits such as the Industrial Area, margins of the Rocky Flats Alluvium, and creek drainages. This decrease in depth to water suggests that these areas are more likely to be associated with groundwater discharge. Depth to water reaches a minimum in the locations of seeps where the depth to water is effectively zero (Plate 7).

Temporal Variations in Saturated Thickness

Annual variations in the saturated thickness of surficial deposits are greatest in the developed areas of the Rocky Flats site (Plate 6). Annual variations in saturated thickness in and immediately adjacent to the Industrial Area are generally greater than 3 feet. At several locations in and adjacent to the Industrial Area, variations in saturated thickness of more than 9 feet have been measured. Large variations in saturated thickness also occur adjacent to the Groundwater Intercept System at the Present Landfill (Plate 6).

Many of the areas exhibiting large fluctuations in saturated thickness appear to be associated with engineered structures. In the Industrial Area, much of the ground surface is impermeable due to the presence of buildings and parking lots (Plate 8). As a result, a greater amount of stormwater runoff is available to permeable areas. Increased infiltration of stormwater runoff may account for the large variations in saturated thickness in some parts of the Industrial Area.

Variations in saturated thickness also occur northeast of Rocky Flats Lake and along drainages at the Rocky Flats site. Along Smart Ditches 1 and 2, South Walnut Creek, and North Walnut Creek, fluctuations in the saturated thickness may result from the periodic movement of water stored in Rocky Flats Lake and the B-series ponds through South Walnut Creek and Smart Ditches 1 and 2.

6.2.1.3 Recharge

An important source of recharge to the UHSU surficial deposits is infiltration of precipitation. The stable isotope composition of groundwater and water-level fluctuations indicate that infiltration of precipitation is the primary source of recharge to UHSU materials (EG&G, 1995b). Nearly 15.5 inches of precipitation falls annually at the Rocky Flats site (Table 3-3), with the majority of the precipitation falling during April, May, and June (EG&G, 1993a). Most precipitation, however, is lost to runoff and evapotranspiration. Portions of the surficial deposits are recharged by infiltration from streams during the dry months of the year in areas where the water-table elevation is lower than the stream-stage elevation (Section 6.5).

The amount of precipitation that infiltrates surficial deposits is affected locally by the physical and hydrologic characteristics of the soils and subsoils. Infiltration through the vadose zone may occur as uniform areal infiltration through interstitial pore spaces or through isolated channels or regions in the soil. In general, the amount and rate of infiltration is controlled by the slope of the ground surface, the amount and type of vegetation present, the permeability of the surficial materials, and the initial water content of the surface materials.

Upward gradients indicate that the weathered bedrock supplies water to the surficial deposits in a few localized areas of the site. However, insufficient data are available to quantify the vertical movement of water in these areas, and the volumes are expected to be relatively low due to the low permeability of the weathered bedrock. Weathered bedrock recharge of the unconsolidated materials is discussed in Section 6.2.3.

Engineered structures also locally provide a source of water to surficial deposits. The ponds and reservoirs constructed in the Rocky Flats area locally recharge surficial deposits (DOE, 1992c). Leakage from the Solar Evaporation Ponds historically may have been a source of recharge to the surficial deposits in OU4, although only two of the ponds contained liquids as of June 1994. Insufficient historical data are available for determining if groundwater levels have decreased in the Solar Evaporation Ponds area since the ponds were drained (DOE, 1994b and 1994e). Recharge to surficial deposits also historically occurred at the East and West Spray Fields, adjacent to the Landfill Pond, and adjacent to some of the impoundment ponds in North Walnut Creek as a result of spray evaporation of wastewater (DOE, 1994d). Currently, wastewater is not treated by means of spray evaporation at the Rocky Flats site.

UHSU groundwater collected from wells near Rocky Flats Lake and the clay pit on the west side of the site is isotopically heavier than groundwater from most other areas at the Rocky Flats site. This suggests that the groundwater contains a component derived from isotopically heavier sources (i.e., sources that have undergone O^{16} depletion due to evaporation) such as Rocky Flats Lake or the clay pit (EG&G, 1995b).

Stable-isotope studies indicate that surface-water bodies located west of the Rocky Flats site provide recharge to the UHSU. These surface-water bodies (one upgradient of the Rocky Flats site) include Rocky Flats Lake and a flooded clay pit.

Additional engineered structures recharging surficial deposits may include footing drains that discharge to the ground surface or directly to the subsurface via leaking pipes. For example, the Building 881 footing drain in OU1 formerly discharged to the ground surface. During the construction of the French drain, the footing drain was connected to the French drain, and water levels in the vicinity of the former discharge point have subsequently dropped (DOE, 1992d). Infiltration from drainage ditches may

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also locally act as a source of recharge. These structures have the potential to locally affect the groundwater system in surficial deposits. For example, in OU1 the former skimming pond locally elevated the water table and caused seeps on the 881 Hillside (EG&G, 1992a).

Macropores have been identified as another mechanism that may result in rapid and increased recharge to surficial deposits. Macropores within the soil column may occur as desiccation cracks, large pores greater than 1 millimeter, root channels, rodent holes, and man-made features. In areas where these features are present in significant amounts, a dual porosity system of macropores and interstitial pores exists. In areas where the water table is shallow, such as OU4, macropores allow water to infiltrate rapidly (relative to the saturated hydraulic conductivities of the surficial deposits) causing changes in water-table elevation as quickly as eight hours after precipitation events (DOE, 1994b).

6.2.1.4 Discharge

Discharge of surficial deposits groundwater occurs by a number of different mechanisms. These include transpiration by vegetation, evaporation in the capillary zone, discharge to seeps and ephemeral streams; and infiltration into the underlying weathered bedrock.

Shallow groundwater is transpired by phreatophytes typically growing near seeps and along streams. In these areas, the water table is closer to the surface, allowing the roots of phreatophytes to reach saturated or nearly saturated areas in the subsurface. Shallow groundwater is also discharged to the atmosphere via evaporation in the capillary zone. Evidence of this evaporation is left in the form of caliche zones in the subsurface. These zones form as a result of the evaporation of groundwater and subsequent precipitation of calcium carbonate in the capillary fringe. Caliche zones also form at or near the surface where seeps are located (DOE, 1994b).

Seeps are important discharge points of groundwater at the Rocky Flats site. Seeps are commonly located at the contact between bedrock and surficial deposits along the slopes of the incised valleys. Examples of contact seeps are present south of Pond B-5 on the hillside and north of the Solar Evaporation Ponds (Plate 9). Seeps may also occur adjacent to outcrops of more permeable zones within the bedrock such as the seeps located south of Pond B-1 in OU2 (Plate 9). The location of seeps is commonly expressed by changes in vegetation (DOE, 1993b).

Groundwater is also discharged to streams in the Rocky Flats area. Discharge to streams varies seasonally and typically decreases during the drier months (Fedors and Warner, 1993). A particular reach of stream may be gaining during the spring and losing during the late summer, fall, and winter. Discharge from streams also varies spatially. The western reaches of the streams are generally gaining for some of the year, while the central or eastern reaches of the streams are more often losing reaches. A detailed discussion of surface-water and groundwater interactions is provided in Section 6.5.

Groundwater from surficial deposits also infiltrates into the underlying weathered bedrock. Locally, both downward and upward hydraulic gradients have been observed between the weathered bedrock and surficial deposits (EG&G, 1994a), indicating that discharge to weathered bedrock varies spatially and temporally. The rate of infiltration is controlled by the vertical hydraulic gradient and the hydraulic conductivity of the units. Section 6.2.3 further discusses interaction between the surficial deposits and the weathered bedrock.

Engineered structures also act as points of discharge for surficial deposits. The French drain along the 881 Hillside and the ITS north of the Solar Evaporation Ponds remove groundwater from the surficial deposits causing them to be locally unsaturated (DOE, 1992d and 1994f). Locally, drainage ditches may also remove water from the surficial deposits (DOE, 1993b). The Groundwater Intercept System also removes groundwater from the surficial deposits upgradient of the Present Landfill (DOE, 1994a).

6.2.1.5 Hydraulic Properties

A thorough review and reanalysis of aquifer tests was performed as part of this study to accurately define the hydraulic properties associated with the UHSU at the Rocky Flats site. Results from packer, slug, and pumping tests were evaluated for usability and reanalyzed in many cases (EG&G, 1994d; Appendix H). As a result of this effort, estimates of saturated hydraulic conductivity for UHSU and LHSU lithologic units were calculated. Estimates of other hydraulic properties such as storativity and effective porosity are not widely available for the Rocky Flats site, and the few values that are available are not considered reliable (Smith, 1994).

The results of the tests were compiled, and geometric means of saturated hydraulic conductivity for different lithologic units of the UHSU and LHSU were calculated. Estimates of saturated hydraulic conductivity were compiled for the following lithologic units: Rocky Flats Alluvium, colluvium, valley-fill alluvium, weathered bedrock claystones, weathered bedrock siltstones, weathered bedrock Arapahoe Formation sandstone, other weathered bedrock sandstones, unweathered claystones, unweathered siltstones, and unweathered sandstones. These values compare favorably to those provided in other documents such as the 1993 Annual RCRA Groundwater Monitoring Report (EG&G, 1994b).

The geometric mean of hydraulic conductivity values for the Rocky Flats Alluvium, colluvium, and valley-fill alluvium are 2.06E-04, 1.15E-04 and 2.16E-03 cm/sec,

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respectively (Figure 6-2). The estimates of saturated hydraulic conductivity reflect the lithology of the individual units. Valley-fill alluvium contains relatively more sand and gravel and, consequently, has a hydraulic conductivity higher than other surficial deposits. The mean saturated hydraulic conductivity values for the colluvium and Rocky Flats Alluvium are essentially the same indicating that they have the same ability to transmit water under a given hydraulic gradient.

Table G-2 summarizes the hydraulic data statistics. The statistics indicate that the Rocky Flats Alluvium is the most heterogeneous unit of the surficial deposits. However, this may be due partially to the fact that the largest number of observations have been collected in the Rocky Flats Alluvium. The median and mean of the hydraulic conductivity data for Rocky Flats Alluvium differ by one order of magnitude, and the minimum and maximum value differ by six orders of magnitude. For normal distributions, the median and mean are roughly equal.

The coefficients of skewness and kurtosis are also used to describe the shape of a distribution. A distribution that is asymmetric can be skewed to the left (negatively skewed) or skewed to the right (positively skewed). If the coefficient of skewness is less than 0.5 and greater than -1.0, the data are not significantly skewed. If the coefficient of skewness is greater than 0.5 the data are positively skewed, and if the coefficient of skewness is less than -1.0, the data are negatively skewed (Stednick, 1991). Kurtosis describes the degree of peakedness of a distribution relative to the length and size of its tails. A kurtosis value between two and four indicates normally peaked (mesokurtic) data; less than two indicates flat (platykurtic) data; and greater than four indicates highly peaked (leptokurtic) data (Stednick, 1991). The skewness and kurtosis of the hydraulic conductivity data for Rocky Flats Alluvium are 3.46 and 12.7, respectively, indicating that the data are positively skewed and leptokurtic. The coefficient of variation (standard deviation/mean) for Rocky Flats Alluvium is 2.44. A coefficient of variation greater than 1 is indicative of significant variation within the data (Jury, 1985).

A large set of hydraulic conductivity values (116) were available for analysis. Thus, the characteristics of the Rocky Flats Alluvium hydraulic conductivity are most likely well represented by this data set. Hurr (1976) estimated the hydraulic conductivity of the Rocky Flats Alluvium to be about 35 ft/d (1.23E-02 cm/sec) compared to a geometric mean of 2.06E-04 for the current data.

Because a significant amount of hydraulic conductivity data is available for Rocky Flats Alluvium, a map is presented showing the spatial distribution of hydraulic conductivity at the site (Figure 6-3). Several estimates of hydraulic conductivity are available for most wells. For these wells, the average of the values is posted. Values are not contoured because of a lack of coverage in many areas. There are wide variations in hydraulic conductivities over relatively short distances; however in general, higher hydraulic conductivities (>1.00E-03 cm/sec) occur in most areas of the site, and the lower conductivities (<1.00E-06 cm/sec) are limited to the central and western portions of the site (Figure 6-3).

Hydraulic conductivity values for valley-fill alluvium are less heterogeneous than values in Rocky Flats Alluvium. The median and mean differ by one order of magnitude, and the minimum and maximum value differ by four orders of magnitude (Table G-1). The coefficient of variation (standard deviation/mean) for hydraulic conductivity values in valley-fill alluvium is 1.12 indicating significant variation within the data. The skewness and kurtosis of the data are 0.68 and -0.89, respectively, indicating that the data are not significantly skewed and platykurtic. A moderate number of values (42) for valley-fill hydraulic conductivity were analyzed, and the characteristics of the valley-fill alluvium are thought to be reasonably well represented by these data. The distribution of saturated hydraulic conductivities in valley-fill alluvium is shown in Figure 6-4.

Statistics indicate that colluvium is the most homogenous of the surficial deposits (Table G-1). The median and mean are approximately equal, and the range of values is approximately two orders of magnitude. The coefficient of variation (standard deviation/mean) for valley-fill alluvium is 1.08. The skewness and kurtosis of the data are 2.14 and 5.63, respectively, indicating that the data are positively skewed and leptokurtic. Though the colluvium appears to be relatively homogenous in terms of hydraulic conductivity, the hydraulic conductivity of the colluvium is characterized by only 15 values and this population may not be large enough to accurately characterize the heterogeneity of the colluvium. The distribution of saturated hydraulic conductivity values in colluvium is shown in Figure 6-5.

Box-and-whisker plots for saturated hydraulic conductivity values from different geologic units are presented in Appendix G. Box-and-whisker plots provide a visual impression of the data and are useful for evaluating outliers. As demonstrated in these plots, the Rocky Flats Alluvium has several values plotted beyond the upper quartile range. The colluvium has only a single outlier value extending beyond the upper quartile range. Conversely, the valley-fill alluvium has no outlier values. Because these hydraulic data were deemed usable through extensive review and reanalysis (refer to Table G-1 and Appendix H), these outliers likely represent heterogeneities in the flow system. The construction of these plots is discussed in detail in Appendix G.

Hydraulic conductivities have also been estimated using permeameter tests. In analyzing these data, the hydraulic conductivity values were separated into three categories: unconsolidated surficial deposits, weathered bedrock, and unweathered bedrock. Hydraulic conductivity values for unconsolidated surficial deposits range

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from 1.20E-08 to 3.60E-03 cm/sec with a geometric mean of 2.24E-04 cm/sec (Table G-3). These hydraulic conductivity values are very similar to those estimated by aquifer tests (EG&G, 1994d).

Estimated well yields for the unconsolidated surficial deposits are presented in Table G-7. Well yields for the different geologic units vary by orders of magnitude. For example, estimated well yields for the Rocky Flats alluvium range from 0.056 gpm to 12.06 gpm. The reported well yields for colluvium are less than 1.0 gpm, ranging from 0.055 gpm to 0.73 gpm. The single reported value for valley-fill alluvium is 1.56 gpm.

Contaminant transport in the surficial deposits is controlled by both advective and diffusive processes depending on the median grain size and average linear groundwater velocity of the unit. Calculations assessing the relative importance of diffusion and advection in the transport of contaminants are provided in Appendix G.

Contaminant transport in the Rocky Flats Alluvium is controlled by either diffusion, advection, or both mechanisms depending on grain size (Figure G-11). Contaminant migration in valley-fill alluvium is controlled by advection in more coarse-grained material and both advection and diffusion in the more fine-grained material (Figure G-5). Colluvium is generally more fine grained than Rocky Flats Alluvium or valley-fill alluvium. Consequently, contaminant transport is controlled by either diffusion or a combination of diffusion and advection in the colluvial deposits (Figure G-11).

6.2.2 Weathered Bedrock

This section discusses the hydrogeology of the weathered bedrock at the Rocky Flats site and includes a description of weathered bedrock geology, the distribution and occurrence of weathered bedrock groundwater, the recharge and discharge relationships within weathered bedrock, and an evaluation of hydraulic properties and flow conditions in weathered bedrock.

6.2.2.1 Geology of Weathered Bedrock

The geology of the weathered bedrock has been summarized in previous studies (EG&G, 1992b) and is discussed in detail in the Geologic Characterization Report (EG&G, 1995a). Bedrock is defined as the first occurrence of consolidated rocks under the surficial deposits (EG&G, 1995a). At the Rocky Flats site, bedrock is composed of the Cretaceous Arapahoe and Laramie formations.

Weathered bedrock is composed of sandstones, siltstones, and claystones and is characterized by an abundance of iron-oxide staining, healed and unhealed fractures, and increased friability in the coarser units. Weathered bedrock is identified by color changes, mottling, and the degree of iron-oxide staining. Fractures appear more extensively in the weathered zones than in unweathered bedrock (EG&G, 1995a). Fractures commonly occur within 15 feet below the top of weathered bedrock, and a few have been found as deep as 100 feet below the top of weathered bedrock (EG&G, 1994a; EG&G, 1993g).

Weathered bedrock underlies the entire Rocky Flats site and ranges from less than 10 feet to more than 60 feet thick. Weathered bedrock is thickest in the western portion of the site and thins to the east. The thickness of weathered bedrock varies less in the western and eastern parts of Rocky Flats than in the central portion of the site. Due to the extensive erosion of the Rocky Flats Alluvium in the eastern portion of the site, much of the weathered bedrock has been removed. In the middle section of the site, erosion is actively incising modern streams into weathered bedrock. In the western portion of the site, the thick mantle of surficial deposits has prevented erosion of the weathered bedrock surface.

In general, locally thicker areas of weathered bedrock may indicate the presence of UHSU sandstones. In OU2 and OU4, weathered bedrock is found beneath weathered sandstones. Locally, weathered bedrock has been found to be thickest in valley bottoms (DOE, 1993b; EG&G, 1992b and 1994a). However, examination of the isopach map of weathered bedrock in the Geologic Characterization Report (EG&G, 1995a) reveals no obvious relationship between areas where weathered bedrock is thicker and modern channels or paleochannels. This apparent discrepancy may be due to the scale of the weathered bedrock map, as compared to the scale of local (OU-wide) investigations.

Sandstones and siltstones within weathered bedrock are commonly lenticular and discontinuous and are usually isolated both vertically and horizontally by thick sequences of claystones and siltstones, although a few isolated, stacked sandstones have been documented (EG&G, 1995a). Sandstones, siltstones, and claystones from both the Arapahoe and the Laramie formations can subcrop together. However, because of stratigraphic and lithologic similarities, it is often difficult to differentiate between the Arapahoe and Laramie Formation siltstones and claystones. These units have similar hydraulic properties; therefore, the stratigraphic labeling of subcropping claystones and siltstones is not necessary for hydrogeologic characterization. These units are grouped together as weathered bedrock claystones and siltstones (EG&G, 1995a). Laramie Formation sandstones also have hydraulic conductivity values similar to weathered siltstones and claystones. However, Arapahoe Formation sandstones have higher hydraulic conductivities than the other weathered bedrock lithologies and will be discussed separately. The hydraulic properties of the weathered bedrock are discussed further in Section 6.2.2.5.

All sandstones that are in hydraulic connection with surficial deposits are considered part of the UHSU (DOE, 1994c and 1993a). Laramie and Arapahoe Formation sandstones occur in weathered bedrock and have distinguishing geologic and hydraulic characteristics. All weathered sandstones not identified as Arapahoe Formation sandstones are referred to as weathered sandstones. Weathered Arapahoe Formation sandstones identified as Arapahoe No. 1 sandstones in previous studies are referred to as Arapahoe Formation sandstones in this report (EG&G, 1995a).

The Arapahoe Formation sandstone has the greatest lateral extent and highest hydraulic permeability of any UHSU sandstone (EG&G, 1995a). The Arapahoe Formation sandstone lies stratigraphically in the upper parts of weathered bedrock and subcrops in areas such as OU4 and OU2. As a general rule, sandstones subcropping on the pediment are usually Arapahoe Formation sandstones, whereas sandstones that subcrop on valley slopes and floors are Laramie Formation sandstones. The Arapahoe Formation sandstone isolith map shows the distribution and thickness of the Arapahoe Formation sandstones (EG&G, 1995a, Plate 5-10).

The top of weathered bedrock is a gently sloping erosion surface or pediment, dipping toward the east. Numerous paleochannels are incised into the top of bedrock and generally follow the same trends as modern drainages. Similar to modern drainages at Rocky Flats, the larger incised paleochannels drained eastward and smaller paleochannels ran north and south toward modern-day stream valleys. Studies in OU2 and OU4 have documented that coarse unconsolidated sediments may fill the paleochannels (EG&G, 1995a). Gravel-lined channels can have hydraulic significance by creating preferential flowpaths within surficial deposits. This is discussed further in Section 6.2.3

The bedrock-surface elevation map shows that paleodrainages project upstream from the headwaters of modern streams (EG&G, 1995a, Plate 4-3). At Antelope Springs, east of Rocky Flats Lake, the top-of-bedrock contour map reveals a paleochannel continuing under the Rocky Flats Alluvium. It appears that the paleochannel may act as a conduit to channel water to Antelope Springs. Other evidence that paleochannels are serving as "pipelines" to guide water to modern streams has been seen in OU2, where head values in the paleochannel indicate discharge toward the seep area. The paleochannel is probably in direct hydraulic connection with the small tributary and associated perennial springs found along the hillside (EG&G, 1993g). Paleochannels in weathered bedrock may also locally contribute water to modern tributaries at other locations at Rocky Flats.

6.2.2.2 *Occurrence and Distribution of Groundwater*

Delineating the occurrence and distribution of groundwater within weathered bedrock is difficult because of the manner in which weathered-bedrock wells are constructed at the Rocky Flats site. Screens for weathered-bedrock wells are commonly preferentially placed near the top of bedrock. This preferential placement of well screens limits the usefulness of the water-level data. Because the weathered-bedrock wells are not screened at the base of the unit, a dry well does not necessarily indicate that the weathered bedrock is completely unsaturated. Therefore, it is difficult to construct accurate sitewide maps of the potentiometric surface and saturated thickness of the weathered bedrock.

Groundwater within weathered bedrock at the Rocky Flats site exists under both confined and unconfined conditions. Groundwater in weathered bedrock sandstones is locally confined in areas where they are overlain by siltstones and claystones (DOE, 1993b). These conditions occur in OU2 and in the Industrial Area (well P207389). Groundwater in the weathered bedrock occurs under unconfined conditions in areas where the water levels in the weathered bedrock and surficial deposits are the same; surficial deposits are unsaturated; the potentiometric surface of weathered bedrock is below the top of bedrock; or surficial deposits groundwater is perched above the weathered bedrock contact.

The volume of water stored in the Arapahoe Formation beneath Rocky Flats was estimated in the Groundwater Protection and Monitoring Program Plan (EG&G, 1991c). This report estimates that the volume of water stored in Arapahoe Formation sandstones and siltstones is 52,200 acre-feet (Table 6-1).

Potentiometric Surface

Potentiometric maps of weathered bedrock have been constructed for OU4 (EG&G, 1994b) and OU7 (DOE, 1994e). These reports show that the potentiometric surface of weathered bedrock generally resembles the potentiometric surface of surficial materials but is slightly lower in most areas. One exception to this occurs in OU2, where a large sandstone unit subcrops. The potentiometric surface of the weathered bedrock sandstone and surficial deposits is essentially the same in this area (DOE, 1993b). Similar conditions are expected in areas where sandstones subcrop beneath the alluvium. Based on the similarities in the potentiometric surface for surficial deposits and weathered bedrock, sitewide flow patterns within the two lithologic units are expected to be similar, and general statements about flow within the weathered bedrock can be made.

Weathered-bedrock groundwater in topographically high ridges is expected to flow generally toward the east-northeast following the surficial deposits flow pattern.

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Evidence of this pattern is shown in potentiometric maps constructed for weathered bedrock in the Solar Evaporation Ponds area in the 1993 Annual RCRA Groundwater Monitoring Report (Figure 6-6) (EG&G, 1994b). In areas where ridges are dissected by the east-northeast-trending stream drainages, groundwater flows to the north or south toward valley bottoms. In the valley bottoms, groundwater flows to the east, generally following the course of the streams. The effect of stream drainages on groundwater flow within weathered bedrock is clearly shown in the potentiometric maps for weathered bedrock at the Present Landfill (Figure 6-7) (DOE, 1994e).

Hydrographs indicate that seasonal variations in precipitation are reflected in some, but not all, weathered-bedrock wells. Wells that show the strongest correlation between water level and seasonal precipitation are typically screened in sandstone (Appendix D, well-cluster hydrographs 2, 19, and 38), but some wells screened in siltstone or claystone also exhibit seasonal variations (well-cluster hydrographs 1, 8, and 41). In some cases, wells screened in weathered claystone and siltstone appear to be influenced by sampling events. The removal of three well volumes of water from the wells prior to sampling (as required by Rocky Flats standard operating procedures) causes significant drawdown in the wells, and the relatively low hydraulic conductivity of the weathered bedrock claystones and siltstones results in long water-level recovery times. Hydrographs indicate that water levels in many weathered bedrock wells do not fully recover prior to the next sampling event (well-cluster hydrographs 10, 15, 20, 46, and 47). Thus, any seasonal fluctuation in water levels in these wells may be masked by sampling-and-recovery patterns.

6.2.2.3 Recharge

The primary sources of recharge to the weathered bedrock are infiltration through the surficial deposits and direct recharge at outcrops in the western portions of the Rocky Flats site (EG&G, 1994a). Geochemical data indicate that surface water also recharges weathered bedrock. Recharge from surface-water bodies may occur indirectly via infiltration of surficial deposits groundwater or directly in areas where weathered bedrock is in direct contact with surface water (EG&G, 1995b).

The Landfill Pond sits directly on weathered bedrock, and potentiometric data indicate that a downward gradient exists in the pond area and that weathered bedrock is recharged by the Landfill Pond (DOE, 1994e). Weathered bedrock is also believed to be in direct contact with surface water beneath some of the ponds constructed in North and South Walnut Creeks. During construction of some of these ponds, all surficial deposits were removed to increase the capacity of the ponds (EG&G, 1993g).

Recharge to the weathered bedrock occurs across the Rocky Flats site but is expected to be greatest where the overlying surficial deposits are perennially saturated. In the western portion of the site, bedrock outcrops are saturated in most areas and precipitation can directly recharge weathered bedrock. In the central and eastern portions of the site, surficial deposits on ridge tops are unsaturated in places limiting recharge to weathered bedrock. Potentiometric data from OU1, OU2, and OU4 indicate that surficial deposits on the hillsides are largely unsaturated (DOE, 1993b, 1994f, and 1994g), and only minor amounts of recharge to weathered bedrock are expected in these areas. In the stream drainages, surficial deposits are typically saturated and downward infiltration of groundwater into the weathered bedrock is expected. Weathered bedrock is also recharged by surface water beneath the Landfill Pond and possibly beneath some of the A- or B-series ponds. At these locations, surface water is in direct contact with the weathered bedrock.

Factors that influence infiltration from the surficial deposits include the vertical hydraulic gradient between surficial deposits and weathered bedrock, the saturated hydraulic conductivity of weathered bedrock, and the presence of an unsaturated zone at the top of bedrock. Vertical hydraulic gradients between surficial deposits and weathered bedrock at the Rocky Flats site are usually downward (Figure 6-8), indicating that groundwater is flowing from surficial deposits into weathered bedrock. However, these calculated gradients are only estimates of the hydraulic conditions present at the site and should be used primarily qualitatively.

The lithology and saturated hydraulic conductivity of weathered bedrock influence the infiltration of groundwater from surficial deposits into weathered bedrock. High hydraulic conductivity units (sandstones) in the weathered bedrock will allow groundwater within surficial deposits to more readily flow into weathered bedrock. For example, the subcropping sandstones in OU4 and OU2 are preferential flowpaths for groundwater (DOE, 1994c and 1993). The occurrence of a subcropping sandstone in OU4 results in the complete desaturation of the overlying surficial deposits (DOE, 1994f). The subcropping lithofacies at the Rocky Flats site were mapped as part of the Geologic Characterization Report (EG&G, 1995a, Plate 5-1).

Hydrographs indicate that unsaturated zones exist at the top of weathered bedrock below saturated surficial deposits in some areas. The occurrence of these unsaturated zones is not limited to any particular setting at Rocky Flats. Where present, these unsaturated zones are generally expected to inhibit the downward movement of groundwater.

6.2.2.4 *Discharge*

Weathered-bedrock groundwater at Rocky Flats is discharged to surficial deposits, to the unweathered bedrock, and to engineered structures. Along the hillsides, the topography of the bedrock surface changes rapidly, causing the weathered-bedrock

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potentiometric surface to intersect the top of bedrock in many places. At these locations, weathered-bedrock groundwater discharges to the surficial deposits, and surface seeps form in some of these areas. For example, a weathered bedrock sandstone subcrops south of Pond B-2 and discharges groundwater to the surficial deposits. As a result, an ephemeral seep is present on the hillside (DOE, 1993b).

Weathered bedrock also discharges to the surficial deposits in a few other localized areas. Well-cluster hydrograph 38 (Appendix D) indicates that there is an upward gradient from the weathered bedrock to the surficial deposits southwest of the Solar Evaporation Ponds (Figure 6-8). At this location, weathered bedrock sandstones are confined by claystones and groundwater is potentially discharging through the confining claystone to the overlying surficial deposits. At another location along Smart Ditch #1, weathered bedrock may periodically discharge to the surficial deposits. Well-cluster hydrograph 8 (Appendix D) shows that the potentiometric surface in the weathered bedrock is occasionally higher than that of the surficial deposits. However, other well-cluster hydrographs located adjacent to streams do not show similar patterns.

Engineered structures may act as discharge points for weathered-bedrock groundwater in some cases. Building footing drains constructed below the top of bedrock are expected to act as discharge points for weathered-bedrock groundwater. Other Groundwater Intercept Systems such as the OU4 ITS and OU1 French drain are not expected to intercept significant amounts of weathered bedrock groundwater because these structures penetrate only the uppermost 1 to 2 feet of the bedrock (DOE, 1994c and 1994g).

Discharge of weathered-bedrock groundwater to surface-water bodies is possible in areas where the weathered-bedrock potentiometric surface is higher than the surface-water elevation. However, there is no indication that these conditions presently occur at the site (Section 6.5).

6.2.2.5 Hydraulic Properties

Estimates of saturated hydraulic conductivity for weathered bedrock were compiled for the following lithologic units: weathered bedrock claystones, weathered bedrock siltstones, weathered bedrock Arapahoe Formation sandstone, and other weathered bedrock sandstones. These values compare favorably to those given in other documents such as the 1993 Annual RCRA Groundwater Monitoring Report (EG&G, 1994b).

The geometric means of hydraulic conductivity values for the weathered bedrock claystones, siltstone, Arapahoe Formation sandstone, and other sandstones are 8.82E-07, 2.88E-05, 7.88E-04, and 3.89E-05 cm/sec, respectively (Figure 6-9). Weathered claystones exhibit the lowest hydraulic conductivity. Weathered siltstones and "other" sandstones have similar hydraulic conductivities and are more permeable than weathered claystones. The Arapahoe Formation sandstones are the most permeable weathered bedrock unit.

The statistics for hydraulic data indicate that weathered bedrock claystones are the most heterogeneous of the weathered bedrock lithologies (Table G-2). The median and mean differ by two orders of magnitude, and the minimum and maximum value differ by four orders of magnitude. The coefficient of variation (standard deviation/mean) for weathered bedrock is 5.66. The skewness and kurtosis of the data are 6.9 and 48.2, respectively, indicating that the data are positively skewed and leptokurtic. The relatively large number of hydraulic conductivity values (49) available for analysis provide an adequate characterization of weathered claystone hydraulic conductivity.

The hydraulic properties of weathered bedrock siltstones are not well characterized by the available data because only three values are available for analysis. However, the three values fall within a narrow range (2.34E-05 to 3.40E-05 cm/sec), and the coefficient of variation is accordingly small (0.184). The skewness of the data is -0.71, indicating that the data are not significantly skewed. There are not enough estimates of weathered bedrock siltstone hydraulic conductivity to calculate the kurtosis of the data.

Weathered sandstones are relatively homogeneous. The median and mean differ by less than one order of magnitude, and the minimum and maximum value differ by two orders of magnitude (Table G-2). However, there are only eight values for non-Arapahoe Formation sandstone hydraulic conductivity. Therefore, the properties of the sandstone may not be well represented. The coefficient of variation (standard deviation/mean) for weathered sandstone's is 1.08. The skewness and kurtosis of the data are 1.06 and -0.54 respectively, indicating that the data are positively skewed and platykurtic.

The Arapahoe Formation sandstone is moderately heterogeneous in terms of saturated hydraulic conductivity. The median and mean differ by one order of magnitude, and the range of values is approximately two orders of magnitude. The coefficient of variation for valley-fill alluvium is 1.26. The skewness and kurtosis of the data are 1.68 and 2.26, respectively, indicating that the data are positively skewed and mesokurtic. The Arapahoe Formation sandstone is characterized by 34 values and, therefore, is thought to be reasonably well characterized.

Box-and-whisker plots for saturated hydraulic conductivity values from weathered bedrock units are presented in Appendix G. Box-and-whisker plots provide a visual impression of the data and are useful for evaluating outliers. As demonstrated in these plots, only the Arapahoe Sandstone and weathered claystones show outliers beyond the upper quartile ranges. Because these hydraulic data were deemed usable through extensive review and reanalysis (refer to Table G-1 and Appendix H), these outliers likely represent heterogeneities in the flow system. The construction of these plots is discussed in Appendix G.

Estimated well yields for weathered bedrock are presented in Table G-4. Well yields for different bedrock units vary by orders of magnitude. For example, the single value of 0.026 gpm for weathered sandstone is significantly less than the range of values (1.62 gpm to 6.14 gpm) for the Arapahoe Formation sandstone.

Contaminant transport in the weathered bedrock is controlled by both advective and diffusive processes depending on the median grain size and average linear groundwater velocity of the unit (Figure G-12). Calculations assessing the relative importance of diffusion and advection during contaminant transport are provided in Appendix G. These calculations indicate that contaminant transport is controlled by diffusion in claystones, by a combination of diffusion and advection in siltstones and non-Arapahoe Formation sandstones, and predominately by advection in the Arapahoe No. 1 sandstones.

6.2.3 Summary of UHSU Groundwater Flow

Groundwater flow within the UHSU at the Rocky Flats site is controlled by both regional and local features. This presentation includes discussion of both general sitewide flow patterns and factors that locally control flow. Several examples from different areas of the site are also presented to provide the reader with an understanding of the different controlling factors that affect groundwater flow within the UHSU and groundwater interactions between the different sub-units of the UHSU.

6.2.3.1 Sitewide Flow Patterns

Groundwater in the UHSU generally flows from west to east across the Rocky Flats site following the regional topography of the bedrock surface and ground surface. The incised valleys in the central area of the site have formed east-west-trending ridges and east-draining valleys that also affect the movement of groundwater in the UHSU. UHSU groundwater is present in the Rocky Flats Alluvium on the ridge tops, in colluvium on the valley sides, in valley-fill alluvium in the valley bottoms, and in the weathered bedrock that underlies all of the surficial deposits. Typical groundwater interactions between these UHSU sub-units are discussed below.

Groundwater flow in the surficial deposits typically follows the topography of the ground surface and relief of the bedrock surface. Along the ridge tops within the Rocky Flats Alluvium, groundwater generally flows to the east with components of flow toward the incised valleys. Groundwater within Rocky Flats Alluvium is discharged as interflow to the colluvium or to the surface at contact seeps along the

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margins of the Rocky Flats Alluvium. Seeps are commonly located in areas where surficial deposits thin at bedrock unconformities near the margins of ridges. In the incised valleys, groundwater flows toward valley bottoms from the colluvium into the valley-fill alluvium. In stream valleys, groundwater in valley-fill alluvium flows to the east down the base of the valley. Groundwater flow along stream drainages represents the most significant potential pathway for the offsite migration of contaminants within groundwater. Table G-9, presented in Appendix G, displays calculated seepage velocities for contaminants occurring in groundwater at the Rocky Flats site. These data indicate that seepage velocities are much greater along stream drainages than in other physiographic settings at Rocky Flats. Influent and effluent conditions occur within the valley-fill alluvium along stream channels. Surface-water and groundwater interactions are dependent on the local hydrology and seasonal variations in precipitation. Surface-water and groundwater interactions are discussed in detail in Section 6.5.

Although no sitewide maps of groundwater flow within the UHSU weathered bedrock are presented in this report, other reports have shown that the shape of the weathered bedrock potentiometric surface closely resembles that of the surficial deposits (DOE, 1994c). Thus, groundwater flow patterns within the weathered bedrock are expected to generally parallel those observed in surficial deposits. Groundwater flow within the weathered bedrock, however, is locally affected by the bedrock lithology and structural features. Groundwater preferentially flows in UHSU bedrock sandstones, and the presence of subcropping sands enhances the amount of interaction between weathered bedrock and surficial deposits. During OU1 field investigations, groundwater was observed in the margins and glide planes of slumps existing in weathered bedrock. In some cases, these features may act as preferential pathways for groundwater flow.

Hydrographs show evidence of the groundwater interaction between the surficial deposits and weathered bedrock. Seasonal variations in water levels occur in both surficial deposits and weathered bedrock at some locations indicating that the two units are hydraulically well connected. For example, well-cluster hydrograph 19 (Appendix D) shows that the water-level variations within the Rocky Flats Alluvium (well 2286) and the weathered bedrock sandstone (well P210189) are very similar. In other areas, however, weathered bedrock sandstones do not appear to be in direct hydraulic connection with surficial deposits (well-cluster hydrograph 45). Although the hydraulic connection between surficial deposits and weathered bedrock sandstones is usually good, the amount of hydraulic connection between surficial deposits and weathered bedrock claystones and siltstones is generally limited. The groundwater within the surficial deposits is perched on weathered bedrock claystone in many areas at the Rocky Flats site (well-cluster hydrograph 26).

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Vertical hydraulic gradients calculated using adjacent wells screened in surficial deposits and weathered bedrock indicate that groundwater generally flows downward into weathered bedrock. (Refer to Appendix D for a discussion of the method used to calculate vertical hydraulic gradients.) Exceptions to this condition occur along the hillsides where weathered bedrock recharges surficial deposits (e.g., OU4 and OU2) or where weathered bedrock sandstones are locally confined (DOE, 1993b). The volume of water flowing into the weathered bedrock from the surficial deposits is dependent on vertical hydraulic gradients and the hydraulic conductivity of weathered bedrock. Because the hydraulic conductivity of weathered bedrock is generally one to three orders of magnitude lower than surficial deposits, the flux from surficial deposits to weathered bedrock is controlled by the weathered bedrock conductivity except in areas where weathered bedrock consists of the Arapahoe Formation sandstone.

A conceptual description of unconfined groundwater flow was developed for the Rocky Flats site as part of the Well Evaluation Report (EG&G, 1994a). That report described three general zones where the characteristics of groundwater flow are distinctive. These zones trend north to south and occupy the western, central, and eastern portions of the site.

The western zone is characterized by a relatively unbroken topographic slope formed on the Rocky Flats Alluvium. In this zone, the thickness of surficial deposits is greatest, water-level fluctuations are minor, and the surficial deposits are rarely, if ever, completely unsaturated. Groundwater in the UHSU flows generally east with slight variations in flow direction along the top of the bedrock surface. The predominantly claystone bedrock impedes downward vertical migration of groundwater and directs flow laterally to the east (EG&G, 1994a).

The central zone has a gently eastward-sloping topographic surface that is incised by east-west-trending drainages. Topographic highs are capped by thick deposits of Rocky Flats Alluvium and flanked by colluvium. Groundwater in the Rocky Flats Alluvium flows along the bedrock surface and either emerges at seeps, flows into hillside colluvium, or migrates vertically into lower lithostratigraphic units (weathered bedrock). The potentiometric surface of groundwater in the UHSU generally resembles the ground and bedrock surfaces. The potentiometric surface slopes gently to the east and more steeply north-northeast and south-southeast along hillslopes of the incised drainage valleys. Groundwater flows from broad areas of recharge located upgradient and on nearby topographic highs toward the erosional limit of Rocky Flats Alluvium. From the limit of Rocky Flats Alluvium deposits, groundwater flows toward creeks in the incised drainages (EG&G, 1994a).

In the central zone, ground and bedrock surfaces affect the movement and occurrence of groundwater more significantly than in the western zone. The incised drainages provide a mechanism for draining the UHSU on the ridges of the central zone. Both the ground and bedrock surfaces slope steeply into the drainages causing seeps on valley sides and groundwater flow toward the streams. The draining of the surficial deposits into stream valleys is responsible for reducing the saturated thickness of surficial deposits in the central portions of Rocky Flats. Because of the relatively thinner saturated thicknesses of surficial deposits in this area, the bedrock topography strongly influences the occurrence, distribution, and movement of groundwater in surficial deposits. Surficial deposits are commonly unsaturated over bedrock ridges and saturated in the bedrock channels or depressions. Bedrock channels also act as preferential flowpaths in the central portion of Rocky Flats. For example, groundwater preferentially flows in bedrock channels in OU2 and OU4. The bedrock ridges in these areas are often unsaturated (DOE, 1993b and 1994b).

The eastern zone is characterized by relatively flat surface topography, the absence of thick alluvial deposits (Rocky Flats Alluvium), and more widespread valley-fill deposits. The ground surface is generally covered by thin deposits of colluvium. Horizontal hydraulic gradients are relatively low, and groundwater in surficial deposits may not flow directly toward the axes of stream valleys. Baseflow to creeks is probably also diminished relative to the central zone as a result of lower horizontal hydraulic gradients.

6.2.3.2 Factors Controlling Groundwater Flow

The principal factors that control the flow of groundwater within the UHSU include bedrock topography, surface topography, bedrock lithology and conductivity, lithology and conductivity of surficial deposits, structural features, engineered structures, seasonal variations in precipitation, and hydraulic gradients. A brief description of the influence of each factor is given below, and specific examples of groundwater flow conditions at Rocky Flats are provided in Section 6.2.3.3.

Bedrock Topography

The configuration of the bedrock surface controls the movement of groundwater at both the regional and local scale. Regional groundwater flow is to the east, reflecting the regional easterly dip on the bedrock surface. In the central area of the site where saturated thickness decreases, the topography of the bedrock surface is of greater importance in affecting local flow patterns. Locally, the topography of the bedrock surface directs flow of groundwater and controls occurrence of unsaturated zones. Surficial deposits above bedrock ridges may be unsaturated, whereas the surficial deposits are usually saturated in bedrock channels. These channels also cause springs in areas where channels intersect steep valley slopes (DOE, 1994f and 1994g).

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Surface Topography

Steep hillsides and variation in the thickness of surficial deposits affect the flow of groundwater at Rocky Flats. Variations in surface and bedrock elevation cause changes in the thickness of surficial deposits. Decreases in the thickness of surficial deposits reduces the total volume of pore space available for water storage. Rapid changes in surface elevation along the hillsides allow groundwater in the weathered bedrock to laterally flow into surficial deposits in some areas. The thickness of the surficial deposits typically decreases along the hillsides causing the potentiometric surface to intersect the ground surface and forming seeps in many areas (DOE, 1993b).

Lithology of Subcropping Weathered Bedrock

Lithology of the uppermost bedrock unit influences the movement of groundwater locally. In most locations at Rocky Flats, the subcropping bedrock lithology is claystone or siltstone. Sandstone subcrops beneath the surficial deposits in some areas greatly enhancing hydraulic connection between weathered bedrock and surficial deposits. Subcropping bedrock sandstones may act as either a source or a sink of surficial deposits groundwater depending on vertical gradients. Typically, subcropping bedrock sandstones that occur on ridge tops drain the surficial deposits, whereas bedrock sandstones that subcrop along hillsides recharge the overlying surficial deposits (DOE, 1993b and 1994b). Plate 5-1 (EG&G, 1995a) shows the lithofacies of subcropping bedrock across the site.

Lithology of Surficial Deposits

The lithology of the surficial deposits, particularly the material directly overlying bedrock, affects the flow of groundwater. In general, gravels and sands have higher hydraulic conductivities than silts and clays. The lithology of the surficial deposits directly overlying bedrock is shown in Plate 4-5 (EG&G, 1995a), gravels and sands lie directly over bedrock in the present stream drainages and other, smaller bedrock channels. Analysis of hydraulic conductivity data shows that these valley-fill deposits are generally more permeable than other surficial deposits. Because the stream valleys are lower and are filled with material of higher permeability, they represent preferential pathways for groundwater flow.

Structural Features

Structural features such as slump blocks or faults may influence the movement of groundwater by providing preferential pathways for groundwater flow. Along the margins of slump blocks, evidence suggests that groundwater preferentially flows along the glide planes of slump blocks (DOE, 1992d).

The presence of faults within bedrock at Rocky Flats has been postulated in the Geologic Characterization Report (EG&G, 1995a). Brecciated zones have been noted during drilling of boreholes near the postulated faults. If faults do exist at Rocky Flats, they could act as either conduits or barriers to lateral and vertical groundwater flow (F. Grigsby, personal communication, 1994). Faults within the predominately claystone and siltstone bedrock at Rocky Flats could act as conduits to groundwater flow if permeable brecciated zones are associated with fault zones. If the plasticity of the claystones and siltstones is high, fractures in fault zones may heal causing the faults to act as barriers to groundwater flow. Additional studies are needed to confirm the presence of faults and determine their effect on groundwater flow at the site.

Engineered Structures

Engineered structures, including groundwater diversion systems, buildings, and impervious zones, and surface-water control structures affect UHSU groundwater conditions at the Rocky Flats site. Groundwater diversion systems currently present at the site include the OU4 ITS, the OU1 French drain, and the OU7 Groundwater Intercept System. These systems intercept groundwater and locally desaturate surficial deposits. Buildings and impervious zones locally prevent the infiltration of precipitation (Plate 8). Footing drains adjacent to buildings may also locally desaturate subsurface materials. Surface-water control structures including the A-, B-, and C-series ponds and all stormwater ditches locally provide additional recharge to the UHSU and, thus, influence groundwater flow. Surface-water and groundwater interactions are discussed in detail in Section 6.5.

Vertical Hydraulic Gradients

Vertical hydraulic gradients were calculated using adjacent wells screened across different water-bearing units. In order to understand the flow conditions in the UHSU, gradients were calculated between surficial deposits and the weathered bedrock. A summary table of all gradients calculated and an explanation of the method used to calculate gradients are presented in Appendix G.

Generally, most vertical hydraulic gradients between the surficial deposits and the weathered bedrock are downward (Figure 6-8), ranging from 0.03 to 1.12. At well-cluster 38 in the Industrial Area, an upward vertical hydraulic gradient of 0.05 exists. At this location, weathered bedrock sandstones are overlain by weathered claystones. Potentiometric data suggest that the claystone locally acts as a confining layer. Groundwater movement from weathered bedrock to surficial deposits has also been documented along the hillsides where weathered bedrock recharges surficial deposits (DOE, 1993b). The flow vectors presented in hydrogeologic cross sections D-D' (Plate

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13) and G-G' (Plate 16) qualitatively show the flow relationships between these two units.

Downward vertical hydraulic gradients greater than 1.0 are indicative of unsaturated flow. However, comparison of hydrographs and the calculated gradients reveals that all calculated gradients greater than 0.6 occur in areas where an unsaturated zone exists at the top of weathered bedrock. At these locations, the surficial deposits groundwater is perched on bedrock of lower hydraulic conductivity. These areas of perched surficial deposits groundwater are not limited to any particular physiographic setting at Rocky Flats and occur in both stream drainages and ridge tops. However, groundwater levels in some weathered bedrock wells may be artificially low due to the long recovery times after sampling (EG&G, 1994a).

Seasonal Variations in Precipitation

Seasonal variations in precipitation cause water levels within the UHSU, particularly in surficial deposits, to vary. During the drier seasons, water levels are lowest. In the eastern and central zones of the Rocky Flats site, large areas of the surficial deposits become unsaturated during dry periods, and groundwater may occur only in topographically lower areas of the bedrock surface. Seasonal variations in the potentiometric surface also affect the occurrence of seeps. Many of the seeps at Rocky Flats are present only during the wetter, spring months (DOE, 1994c).

6.2.3.3 *Examples of Groundwater Flow Conditions in the UHSU*

In this section, summaries of the UHSU groundwater systems at several OUs are presented to demonstrate the groundwater flow conditions at Rocky Flats. Emphasis is placed on the factors that affect groundwater flow and the interaction between UHSU sub-units. The reader should refer to the referenced reports for a complete description of the groundwater systems discussed below.

Operable Unit Number 1

OU1 is located along the hillside south and southeast of Building 881. At this location, Rocky Flats Alluvium is present at the top of the hillside, colluvium and artificial fill cover the hillside, and valley-fill alluvium is present in the stream drainage at the base of the hillside. The surficial deposits are underlain by claystone, siltstone, and sandstone of the Laramie Formation (DOE, 1994g).

The primary factors affecting groundwater flow at OU1 are slump features, bedrock topography, lithology of the surficial deposits, and the presence of engineered structures. Bedrock topography is displayed in Figure 6-13. Fine-grained bedrock

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sandstones subcrop beneath the surficial deposits but are not laterally extensive and do not significantly affect groundwater flow in OU1 (DOE, 1994g).

Slump features present along the 881 Hillside influence groundwater movement and surface-water and groundwater interaction. During the installation of the French drain, caliche-rich zones were found in both surficial deposits and weathered bedrock. In surficial deposits, caliche zones bounded apparent slump blocks indicating that flow previously occurred in the glide planes and disrupted zones. Caliche zones in the bedrock were found in the slump glide planes as well. Some small amounts of seepage were observed from the glide planes indicating that groundwater may preferentially reside in the disturbed materials with potentially higher permeability associated with slumps. However, little groundwater movement is expected through these bedrock features because the high plasticity of the claystone is expected to permit healing of the fractures and voids caused by slumping (DOE, 1994g). Figure 6-14 delineates the potential groundwater conditions associated with a typical slump.

The location of slumps may be related to the location of seeps in OU1. Near the head region of slumps, seeps and water-tolerant vegetation such as cattails have been noted. Groundwater may be flowing from depressions in the bedrock surface near the head region of the slumps causing seeps. Other surface seeps appear to be related to slump margins (DOE, 1994g).

Bedrock depressions or paleoscours along the hillside influence the movement of groundwater. Areas where the saturated thickness of the surficial deposits is greater are commonly associated with local bedrock surface depressions (Figures 6-13 and 6-15). These bedrock lows may represent paleochannels or may be associated with the lateral margins or head regions of slumps. Groundwater preferentially flows in these lower areas toward Woman Creek. The OU1 French drain was installed to intercept the flow of groundwater along these pathways (DOE, 1994g).

Excavation for construction of the French drain exposed a large cross section of the UHSU which was studied in detail. During excavation activities, groundwater was discharged into the trench from both sandy, gravelly layers underlain by bedrock and by sandy, silty clay lenses that were bounded by denser clays or claystones. Dry zones within bedrock directly below saturated lenses of surficial deposits were also noted. These observations indicate that UHSU groundwater flows preferentially in these relatively coarse-grained horizons (DOE, 1994g).

Engineered structures including the French drain and the footing drain for Building 881 affect groundwater conditions at OU1. Prior to construction of the French drain, the footing drain for Building 881 discharged to surficial deposits on the hillside. The footing drain is now hydraulically connected to the French drain, effectively removing

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a source of recharge to the UHSU. The French drain was designed to intercept groundwater in the surficial deposits flowing toward Woman Creek. By installing the French drain, both a source of groundwater and existing groundwater are removed from the surficial deposits in OU1. As a result, the volume of groundwater in the surficial deposits has decreased (DOE, 1994g).

Operable Unit Number 2

OU2 is located near the southeast perimeter of the Industrial Area of the Rocky Flats site (Figure 6-10) and includes the 903 Pad, East Trenches, and East Spray Fields. Most of OU2 is situated on an east-west-trending ridge bounded to the south by the Woman Creek drainage and to the north by South Walnut Creek (DOE, 1993b).

At OU2, surficial deposits of the Rocky Flats Alluvium cap a bedrock ridge, whereas flanks of the ridge, or valley sides, are covered with thinner deposits of colluvium (Figure 6-10). A paleochannel, known as the medial paleoscour, trends northeast and cuts down into claystone and Arapahoe Formation sandstone (Figure 6-10). The bedrock surface is also cut by smaller paleochannels on top of the ridge and by "paleogullies" along the south side of the ridge (DOE, 1993b). Figure 6-10 shows a schematic north-south cross section through the OU2 pediment.

Groundwater flow conditions in OU2 typify the hydrogeologic setting of the central zone of the Rocky Flats site. The primary factors affecting groundwater flow in OU2 are bedrock topography, bedrock lithology, and surface topography. Bedrock topography locally directs the flow of groundwater within the surficial deposits and controls the occurrence of saturated and unsaturated areas. Groundwater in the surficial deposits flows primarily toward and within the medial paleoscour because of the relatively higher permeability of the surficial deposits relative to weathered bedrock. The bedrock ridges bounding the paleoscour restrict groundwater outflow to the north and south, particularly during the drier seasons when the water table is lowest (Figures 6-1, 6-10, and 6-11). Groundwater, however, sometimes flows over the southern bedrock ridge toward Woman Creek during high-water conditions in the spring. The saturated thickness of the surficial deposits is greatest along the axis of the paleochannel, whereas some parts of the bounding bedrock ridges are always unsaturated (DOE, 1993b).

The lithology of subcropping bedrock affects the amount of interaction between the surficial deposits and bedrock portions of the UHSU at OU2. The Arapahoe Formation sandstone subcrops directly beneath the Rocky Flats Alluvium along portions of the medial paleoscour and beneath the colluvium on the hillside facing South Walnut Creek and Woman Creek. Potentiometric data indicate that groundwater flows from the Rocky Flats Alluvium to the underlying Arapahoe Formation sandstone in the

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medial paleoscour. Figure 6-12 shows the hydrographs for three wells screened in the Arapahoe Formation sandstone. The water level decreases away from the limit of the sandstone subcrop indicating that groundwater flows away from the medial paleoscour in the sandstone. In addition, water-quality data indicate that VOCs in surficial deposits groundwater have migrated into the Arapahoe Formation sandstone in locations where the sandstone subcrops (DOE, 1993b).

Groundwater flow within the sandstone is controlled by the geometry of the sandstone and the location of subcrops. Potentiometric-surface maps (Plates 2 and 3) indicate that flow in the Arapahoe Formation sandstone diverges from where it subcrops the Rocky Flats Alluvium to the north, northeast, and southeast. Groundwater in the sandstone flows toward the Woman Creek and South Walnut Creek drainages. At these locations, groundwater discharges as interflow to the colluvium and causes surface seeps (Figures 6-1 and 6-11) (DOE, 1993b).

Seeps in OU2 are also caused by bedrock and surface topography. A large seep along South Walnut Creek is caused by discharge of groundwater from the northeast end of the paleoscour. At this location, the bedrock channel acts as a source of groundwater to the hillside. The location of other surface seeps at OU2 is controlled by surface topography. In some locations along the hillsides, the elevation of the ground surface changes more rapidly than that of the water table, and the ground surface intersects the water table forming seeps at these locations (DOE, 1993b).

Operable Unit Number 7

OU7 is located north of the Industrial Area at the upper reaches of the No Name Gulch drainage. OU7 is situated on a gravel-capped pediment which is dissected by Rock Creek to the north and North Walnut Creek to the south. Included within OU7 are the Present Landfill, the Inactive Hazardous Waste Storage Area, the Landfill Pond, and adjacent spray evaporation areas (DOE, 1994e).

Surficial deposits and weathered bedrock are the two water-bearing lithostratigraphic units that compose the UHSU at OU7. Surficial deposits include the Rocky Flats Alluvium, colluvium, valley-fill alluvium, and artificial fill. Rocky Flats Alluvium caps the ridge north and south of No Name Gulch. Colluvium is present on the hillslopes surrounding the Landfill Pond and No Name Gulch. Deposits of valley-fill alluvium are located in the No Name Gulch stream channel. Artificial fill comprises excavated gravels from nearby stockpiles, construction materials, and landfill debris. Artificial fill covers the westernmost extent of the No Name Gulch drainage within the boundaries of the Present Landfill (DOE, 1994e).

Groundwater flow also occurs within weathered bedrock of the undifferentiated Arapahoe and Laramie formations. Weathered bedrock generally comprises claystone and interbedded siltstones. However, a fine-grained, silty sandstone subcrops beneath the valley-fill alluvium downgradient of the Landfill Pond embankment. Borehole data suggest that this sandstone is discontinuous and pinches out a few hundred feet downstream (DOE, 1994e).

The Groundwater Intercept System around the perimeter of the landfill was designed to divert groundwater within the surficial deposits away from the landfill to minimize the generation of waste leachate. The Groundwater Intercept System is a combination of engineered structures that includes a subsurface drainage system, leachate collection system, and two slurry walls (Figure 6-16). Groundwater elevation and geochemistry data indicate that the Groundwater Intercept System is marginally effective in diverting groundwater away from the landfill (DOE, 1994e). Apparently, groundwater inflow occurs on the north side of the landfill where a 444-foot-long breach in the system was identified. Geological and geophysical data suggest that the Groundwater Intercept System on the north side of the landfill is not keyed into bedrock, inferring that groundwater inflow occurs underneath the Groundwater Intercept System. Potentiometric data indicate that groundwater/leachate flow within the landfill is controlled by the topography of the weathered bedrock surface and that the potentiometric surface resembles the configuration of the buried drainage (Figure 6-17). Groundwater/leachate within the surficial deposits is directed toward the center of the buried drainage where it eventually discharges at a seep located at the toe of the landfill or as baseflow to the Landfill Pond (DOE, 1994e).

Groundwater within the weathered bedrock does not appear to be affected by the Groundwater Intercept System. However, similar to groundwater flow within surficial deposits, the configuration of the potentiometric-surface map (Figure 6-7) indicates that groundwater within weathered bedrock is controlled by the bedrock topography and flows toward the center of the Landfill Pond drainage. Groundwater elevation data show that there is a downward component of flow from the surficial deposits groundwater system. The presence of contamination within the weathered bedrock confirms that there is hydraulic connection with the overlying surficial deposits. Groundwater elevation data also indicate that the weathered bedrock locally receives recharge from the Landfill Pond (DOE, 1994e).

6.3 Lower Hydrostratigraphic Unit

The LHSU at the Rocky Flats site consists of low-permeability, unweathered bedrock of the Arapahoe and Laramie formations. A discussion of the occurrence and distribution of LHSU groundwater, LHSU recharge and discharge, and hydraulic properties within the LHSU is presented to provide a conceptual understanding of groundwater flow patterns within the LHSU.

6.3.1 Geology of the LHSU

The Arapahoe and Laramie formations consist primarily of claystone with lesser amounts of siltstone and sandstone. These formations were deposited in a low-energy, fluvial and delta-plain setting, which typically produces a high percentage of fine-grained materials such as clays and silts. A relatively small percentage of sandstone exists within the unweathered bedrock.

The sandstones are likely to have been deposited as channel, bar, and flood-plain deposits (EG&G, 1995a). Individual sandstones can be stacked by vertical aggradation, but most are separated from each other by a substantial thickness of claystone. Where these sandstones are isolated, groundwater flow will be largely controlled by the surrounding deposits of low permeability. The channel sandstones are characterized by lenticular, shoestring geometries. These characteristics tend to decrease hydraulic conductivity in the vertical dimension and laterally across the dip direction (perpendicular to channel axis).

Unweathered bedrock exhibits lower permeability than the overlying weathered bedrock and surficial deposits (Figure 6-18). The contrast in permeability between UHSU deposits and LHSU bedrock differentiates the LHSU from the UHSU. The LHSU begins at the uppermost low-permeability boundary within the bedrock, which is the base of weathering. Higher permeability bedrock deposits that are in hydraulic connection with the overlying alluvial deposits such as weathered bedrock and subcropping sandstones are part of the UHSU.

Other geologic information relevant to conceptualization of LHSU groundwater occurrence and flow includes the potential for faulting. Faults have been mapped in several areas surrounding the Rocky Flats site; typically they trend toward the northeast. For example, northeast-trending faults have been mapped at the Boulder-Marshall Landfill, located northeast of the Rocky Flats site. Offset along these faults has placed claystones of the Laramie Formation against sandstones of the Laramie/Fox Hills aquifer. This structural configuration has significantly restricted lateral flow, as evidenced by anomalous water-table elevations in this area (Fox Consultants, 1984).

Recent geologic investigations at the Rocky Flats site have identified several north- to northeast-trending faults in the shallow bedrock. These faults are described in the companion Geologic Characterization Report (EG&G, 1995a). Fault displacement appears to range from 10 to 120 feet, based on structural cross sections and bedrock structure contours.

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In addition to displacement, faulting can produce a zone of fracturing. Fractures may be open or completely filled with mineral precipitates derived from groundwater or percolation of meteoric water. The nature and degree of fracture fill and interconnectedness of the fracture system determines the degree to which fracturing enhances or reduces permeability.

In Arapahoe Formation sandstones, fault-related, small-scale displacements have been shown to exhibit cataclastic textures resulting from brecciation of sand grains during faulting (Jamieson and Stearns, 1982). These cataclasites have the appearance of gouge-filled fractures. The gouge surfaces may become interconnected and form a zone of increased or reduced permeability. As sandstones become more cemented and compacted, the contribution of fractures to the materials permeability increases. Many sandstones have higher horizontal than vertical permeabilities. However, this may be reversed in highly fractured sandstones by a preference for higher fracture permeability in the vertical direction (Freeze and Cherry, 1979). In general, matrix porosities are greater than fracture porosities and fracture porosities probably decrease with depth.

Recent drilling along a northeast-oriented inferred fault just north of the Landfill Pond (OU7) suggests enhanced permeability along the inferred fault. Two boreholes that did not intercept the fault remained relatively dry following drilling, while a third borehole drilled closer to the inferred fault encountered a highly fractured zone that immediately filled with water (F. Grigsby, personal communication, 1994).

6.3.2 Groundwater Occurrence and Distribution

Groundwater in the LHSU exists within interstitial pore spaces, fractures, and possibly faults. Groundwater in the LHSU can be either confined or unconfined, depending on location. In many cases, however, it is difficult to make this determination because a discrete confining unit is not present. The UHSU exists because of a permeability difference between the UHSU and LHSU rather than the existence of a discrete confining layer. In general, water levels of wells screened in the LHSU are above screened intervals and are occasionally above the top of bedrock. However, the interpretation of hydrographs is difficult because of the effect of sampling on water levels. Groundwater may appear to be unconfined following sampling events when water levels drop below the top of the unweathered bedrock (well-cluster hydrograph 14, Appendix G).

Potentiometric elevations within the LHSU were not contoured because potentiometric data are limited and because isolated sandstone units are preferentially screened in LHSU wells. LHSU wells screened in isolated sandstones represent only local hydraulic conditions and not conditions throughout the LHSU. In general, groundwater flow within the LHSU has a strong downward component as indicated by well-cluster hydrographs 53 and 55 (Appendix D). Locally, upward vertical gradients between unweathered bedrock and UHSU materials can exist in valley bottoms (see well-cluster hydrographs 8, 9, and 10, Appendix D). On the regional scale, flow in the LHSU is from west to east as indicated by the potentiometric-surface map for the Arapahoe aquifer shown in Figure 4-3.

6.3.3 Recharge

Recharge to the LHSU can occur directly from precipitation in the western portions of the Rocky Flats site where bedrock outcrops or as infiltration from the UHSU. In most areas the vertical gradient between the UHSU and the LHSU is downward, indicating the potential for downward recharge (Figure 6-19). This downward component of flow is schematically shown in hydrogeologic cross sections D-D' (Plate 13) and G-G' (Plate 16). Due to the limited amount of potentiometric data in the LHSU, the magnitude of downward flow cannot be inferred from these cross sections. However, the low permeability of LHSU deposits limits the volume of water recharging the LHSU from the UHSU. This interpretation is supported by geochemical information which shows that the UHSU and LHSU groundwater have larger distinct chemistries (EG&G, 1995b). Groundwater from the LHSU is characterized as sodium-sulfate to sodium carbonate, whereas UHSU groundwater is characterized as calcium-bicarbonate. Also, major-ion concentrations in LHSU groundwater exhibit larger variations than in UHSU groundwater. This variation may reflect greater isolation between water-bearing zones in the LHSU (due to isolated regions of flow within low-permeability material). Anthropogenic analytes present in the UHSU are rarely detected in the LHSU (EG&G, 1995b). These distinctions in groundwater chemistry support the concept of limited LHSU recharge from UHSU groundwater.

6.3.4 Discharge

Water-level elevations in LHSU wells indicate that, in general, the horizontal hydraulic gradient within the LHSU follows the regional eastward gradient. This can be seen by examining average water-level elevations in LHSU wells displayed in well-cluster hydrographs 1, 8, and 10 (Appendix D), which indicate lower water-level elevations from west to east across the site. Because gradients reflect the direction of recharge to discharge, an eastward discharge of water through the LHSU is indicated.

Locally, upward gradients from the LHSU to the UHSU exist in stream drainages (well clusters 8, 9, and 10, Appendix D). Upward vertical gradients in stream drainages result from the lower head potential of the UHSU in these areas. Water-level elevations in the LHSU are less affected by changes in surface topography, and LHSU groundwater may locally discharge to the UHSU in stream drainages. However, the

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volume of groundwater discharging to the UHSU would be limited by the low permeability of LHSU materials.

The LHSU may also discharge to the underlying Laramie/Fox Hills aquifer. However, the upper portion of the Laramie Formation is composed predominantly of claystone and forms a confining unit (see Section 4.5). At Rocky Flats, the upper Laramie Formation unit has been estimated to be 300 to 500 feet thick. This unit probably limits LHSU discharge into the Laramie/Fox Hills aquifer due to its low permeability and thickness.

6.3.5 Hydraulic Properties

The results of aquifer tests were compiled, and geometric means of saturated hydraulic conductivity for different lithologic units of the LHSU were calculated (Table G-1). Estimates of saturated hydraulic conductivity were compiled for unweathered bedrock claystones, siltstones, and sandstones. Figure 6-20 shows that the geometric mean of hydraulic conductivity values for LHSU claystones, siltstones, and sandstones are 2.48E-07, 1.59E-07, and 5.77E-07 cm/sec, respectively (EG&G, 1994d). These estimates of saturated hydraulic conductivity indicate that LHSU sandstones are only slightly more permeable than LHSU claystones and siltstones. This indicates that flow rates in the LHSU are only marginally impacted by changes in lithology.

The statistics computed for hydraulic data (Table G-2) show that unweathered claystone is the most heterogeneous unit of the LHSU. The median and mean differ by two orders of magnitude, and the minimum and maximum value differ by five orders of magnitude. The coefficient of variation (standard deviation/mean) for unweathered claystone is 12.2. The skewness and kurtosis of the data are 12.6 and 160 respectively, indicating that the data are positively skewed and leptokurtic. The large variations in hydraulic conductivity may be caused by variations in secondary porosity (such as fractures) within the claystone. A large set of hydraulic conductivity values (160) were available for analysis indicating that unweathered claystone hydraulic conductivity is well characterized.

The hydraulic conductivities of both siltstones and sandstones in the LHSU are heterogeneous. The median and mean of each unit differ by one order of magnitude, and the minimum and maximum value of each unit differ by three orders of magnitude (Table G-2). The coefficients of variation for unweathered siltstone and unweathered sandstone are 2.47 and 2.85, respectively. The skewness of the siltstone and sandstone data is 3.2 and 4.4, respectively. The kurtosis of unweathered bedrock hydraulic conductivities for siltstone and sandstone is 10.4 and 21.1, respectively. Thus, both the unweathered siltstone and sandstone data are positively skewed and leptokurtic. A

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moderate number of values for LHSU siltstones (39) and sandstones (41) were analyzed; therefore, the characteristics of these units are reasonably well characterized.

Box-and-whisker plots for saturated hydraulic conductivity values from different unweathered bedrock units are presented in Appendix G. The unweathered claystones, siltstones, and sandstones all exhibit saturated hydraulic conductivity values that exceed the upper quartile ranges. Because these hydraulic data were deemed usable through extensive review and reanalysis (refer to Table G-1 and Appendix H), these outliers likely represent heterogeneities in the flow system.

Estimated well yields for different lithologic units are presented in Table G-4. The single well yield value of 0.021 gpm for unweathered sandstone is significantly less than reported values for the UHSU.

Contaminant transport in the unweathered bedrock is controlled primarily by diffusion because of the relatively low average linear groundwater velocities within the unit (Figure G-13). Calculations supporting this conclusion are presented in Appendix G.

6.3.6 Summary

The LHSU at the Rocky Flats site is composed of low-permeability, unweathered bedrock of the Arapahoe and Laramie formations. The Arapahoe and Laramie formations consist primarily of claystone with lesser amounts of siltstone and sandstone. These units exhibit lower permeability than the overlying weathered bedrock and surficial deposits that comprise the UHSU. Higher permeability bedrock deposits that are in hydraulic connection with the overlying alluvial deposits (e.g., subcropping sandstones) are part of the UHSU.

Groundwater in the LHSU can be either confined or unconfined and exists within interstitial pore spaces, fractures, and possibly faults. On the regional scale, flow in the LHSU is from west to east. Locally, groundwater flow within the LHSU may be affected by faults and fracture zones within the bedrock. The degree to which the fracture fill and interconnectedness of the fracture system enhances or reduces permeability is unknown.

Recharge to the LHSU can occur directly from precipitation in the western portions of the Rocky Flats site where bedrock outcrops or as infiltration from the UHSU. In most areas, there is potential for downward recharge where the vertical gradient between the UHSU and LHSU is downward. However, distinctions in groundwater chemistry data between the UHSU and LHSU indicate there is limited LHSU recharge from UHSU groundwater.

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Discharge to the UHSU from the LHSU may locally occur in stream drainages where upward gradients have been observed. Discharge does not likely occur downward into the underlying Laramie/Fox Hills aquifer because the upper portion of the Laramie Formation is composed primarily of low-permeability claystone which has been estimated to be 300 to 500 feet thick.

The geometric mean of hydraulic conductivity values for LHSU claystones is 2.48E-07 cm/sec, the hydraulic conductivity of LHSU siltstones is 1.59E-07 cm/sec, and the hydraulic conductivity of LHSU sandstones is 5.77E-07 cm/sec. These close values indicate that flow rates in the LHSU are only marginally impacted by changes in lithology. Contaminant transport in the unweathered bedrock is controlled primarily by diffusion because of the relatively low average linear groundwater velocities within the unit.

6.4 UHSU\LHSU Interactions

The degree of hydraulic interaction between the UHSU and LHSU at the Rocky Flats site is a function of the hydrostratigraphy of the two units. The hydraulic interaction between the hydrostratigraphic units is important in assessing the vertical movement of groundwater and contamination between the hydrostratigraphic units and the potential offsite migration of contaminated groundwater. The interactions between the UHSU and LHSU are examined by discussing the hydraulic properties of the two units, the potential for vertical flow between the two units, the major-ion chemistry and stable isotope composition of the two units, the presence of contamination in the LHSU, and the potential for vertical groundwater movement through secondary permeability such as faults or fractures.

6.4.1 Hydrostratigraphy of the Upper and Lower Hydrostratigraphic Units

The upper and lower hydrostratigraphic units represent the two shallowest groundwater flow regimes at the Rocky Flats site. The UHSU comprises unconsolidated surficial deposits which consist of the Rocky Flats Alluvium, colluvium, valley-fill alluvium, artificial fill, weathered bedrock of the Arapahoe and Laramie formations, and Arapahoe Formation sandstones in hydraulic contact with surficial deposits. The LHSU comprises unweathered bedrock of the Arapahoe and Laramie formations.

The hydrogeologic cross sections and profiles (Plates 10 through 20) illustrate the hydrostratigraphy of the UHSU and LHSU. The contact separating the two hydrostratigraphic units is identified as the base of the weathered zone in the Arapahoe and Laramie formations. Generally, the base of the UHSU gently slopes toward the east, reflecting the relief of the surface topography. The UHSU is thickest on the ridge tops and becomes relatively thin along the stream valleys. The relatively low saturated hydraulic conductivity (10^{-7} cm/sec) of the unweathered claystones and siltstones

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indicates that the LHSU acts as an effective hydraulic barrier to downward migration of groundwater from the UHSU. However, there are saturated sandstone units within the LHSU that may enhance hydraulic interaction with the overlying UHSU. For example, in OU2 LHSU sandstones either subcrop on hillslopes or are within close vertical proximity of the UHSU (DOE, 1993b). The lithology and hydraulic properties of the UHSU and LHSU are discussed in greater detail in Sections 6.2 and 6.3.

6.4.1.1 Well-Cluster Hydrographs

Thirty well-cluster hydrographs demonstrate the hydraulic interactions between the UHSU and LHSU by displaying water-level fluctuations in each unit (Appendix D). The well-cluster data were used for a qualitative assessment of hydraulic interaction between the UHSU and LHSU based on well-completion intervals and potentiometric data. Figure 6-21 shows the locations of the 30 well clusters in relation to the hydrography at the Rocky Flats site.

The majority (25 out of 30) of the LHSU hydrographs do not show seasonal water-level fluctuations similar to those displayed in the UHSU. The completion depths of these LHSU wells range from approximately 25 to 146 feet below the bedrock contact. These wells are spaced randomly throughout the site, located on ridge tops and within drainages. One well cluster (52), completed approximately 44 feet below the bedrock contact, exhibits constant unsaturated conditions. These data suggest that in general the two units are not in direct hydraulic connection. The difference in hydrograph responses are probably a reflection of the contrast in lithology and hydraulic properties between the two units. In some cases, analysis of LHSU water-level data is complicated by abrupt downward shifts in (hydraulic) head followed by slow gradual recovery to static conditions. This is most likely caused by sampling events. The slow recovery time observed on the hydrographs demonstrates the relatively low hydraulic conductivity and slow recharge rates of the LHSU.

Two well clusters (53 and 55) demonstrate hydraulic interactions within the LHSU. The hydrographs of well clusters 53 and 55 display water levels of LHSU wells completed at various depths. Well cluster 53 has three wells completed in the LHSU at depths of approximately 48, 74, and 122 feet below the bedrock contact. These wells show a consistent downward gradient with the two deepest wells showing similar changes in head. The LHSU wells at well cluster 55 are completed at depths of approximately 86 and 108 feet below the bedrock contact. The water levels displayed in these wells show nearly identical changes in head. These well-cluster hydrographs show that changes in head in the LHSU wells are of approximately the same magnitude and frequency suggesting that the LHSU functions as one unit at these locations.

Of the 30 well-cluster hydrographs evaluated, only three displayed similar changes in water-level fluctuations between UHSU and LHSU wells. Well clusters 6, 14, and 35 exhibit seasonal water-level fluctuations in the LHSU that correlate with water-level changes observed in the UHSU. The magnitude of these water-level fluctuations reflect storage changes in the two units. The similarity in frequency and magnitude of storage changes within the two hydrostratigraphic units suggest a hydraulic connection between these two units. The following observations were noted at each of these well clusters:

- Well cluster 6 is located in South Walnut Creek near OU4. The LHSU well is completed in unweathered sandstone and claystone approximately 28 feet below the contact between the bedrock and overlying surficial deposits. The magnitude of the storage changes within the LHSU is slightly less than that of the overlying UHSU, indicating a possible hydraulic connection between the two hydrostratigraphic units at this location.

- Well cluster 14 is located in OU2. The LHSU well is completed in unweathered claystone approximately 42 feet below the contact between the bedrock and the overlying alluvium. The LHSU and UHSU (surficial deposits) wells showed an abrupt decrease in storage in 1990, approximately the same time spray evaporation activities in OU2 ceased. The decline in water levels in the LHSU well is less dramatic than in the UHSU, implying that some recharge may have been reaching the LHSU during spray-evaporation activities.

- Well cluster 53 is also located in OU2. There are three LHSU wells completed at depths of approximately 48, 74, and 122 feet below the bedrock contact at this well cluster. The uppermost LHSU well exhibits slight seasonal cyclic fluctuations similar to those observed in the UHSU, while the two deeper wells do not appear to be hydraulically connected to the UHSU. The shallow LHSU well is completed in unweathered silty sandstone and siltstone. The seasonal water-level fluctuations in the shallow LHSU well subtly reflect the storage changes in the overlying UHSU, indicating that limited hydraulic connection between the two hydrostratigraphic units may only exist at the shallowest depth.

Based on these observations, the LHSU appears to have only limited hydraulic connection with the UHSU and only at shallow depths (within 50 feet of the weathered bedrock/unweathered bedrock contact) in some areas. As demonstrated by the two well clusters in OU2 and the well cluster on the 881 Hillside, hydraulic connection between the hydrostratigraphic units is enhanced in areas where LHSU sandstones subcrop or are within close vertical proximity of the base of the UHSU. It is quite possible that the permeability of the claystone may be enhanced by interconnected fracturing within the unit (discussed in greater detail in Section 6.4.5) Some limited hydraulic connection between the two units is further confirmed by the presence of low concentrations of

VOCs such as benzene, ethyl benzene, and trichloroethane in the LHSU at well clusters 6 and 53.

6.4.1.2 *Hydraulic Properties*

The rate and magnitude of downward seepage from the UHSU to the LHSU is a function of the permeability of the LHSU and the downward hydraulic gradient between the hydrostratigraphic units. Saturated hydraulic conductivity values for the LHSU (10^{-7} cm/sec) are generally two orders of magnitude less than the overlying weathered bedrock strata (10^{-5} cm/sec). The saturated geometric mean hydraulic conductivity values within the LHSU (Table G-2) show slight variation between lithologic units (e.g., unweathered siltstone 1.59E-07 cm/sec, unweathered claystone 2.48E-07 cm/sec, and unweathered sandstone 5.77E-07 cm/sec). The saturated hydraulic conductivity values of these three lithologic units are within the same order of magnitude, suggesting that the rate of groundwater movement within the LHSU remains relatively constant despite changes in lithology. However, vertical saturated hydraulic conductivities may be less than 10^{-7} cm/sec. Anisotropy of the LHSU is demonstrated by results of falling-head permeameter tests presented in Table G-3. The geometric mean of the vertical saturated hydraulic conductivity values is 5.83E-08 cm/sec, an order of magnitude less than the horizontal saturated hydraulic conductivity values presented in Figure 6-20. The range of vertical saturated hydraulic conductivity values (10^{-6} cm/sec to 10^{-10} cm/sec) indicates that the LHSU acts as an effective hydraulic barrier to downward groundwater flow.

Vertical hydraulic gradients determine the direction of flow between the UHSU and LHSU. Of the 11 well clusters used to calculate vertical hydraulic gradients, seven indicated downward flow (Figure 6-19), downward gradients range from 0.03 to 1.00 (Table D-1). Generally, the well clusters showing downward gradients are located on the ridge tops between the incised drainages.

Three of the well-cluster hydrographs (8, 9, 10) exhibited consistent upward gradients; gradients range from 0.02 to 0.24 (Table D-1). These well clusters are located in or near stream channels (Figure 6-19). The upward gradients indicate that LHSU groundwater may recharge the UHSU locally.

It is possible to estimate the magnitude of downward vertical flow into the LHSU from the UHSU using Darcy's law. Assuming homogeneous, isotropic, steady-state, one-dimensional flow and full saturation, downward seepage through the LHSU can be estimated. Using a vertical saturated hydraulic conductivity value of 5.83E-08 cm/sec (geometric mean for the LHSU from Table G-3), a hydraulic gradient of one, and Darcy's law, the downward flux is estimated as:

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$$q = K\frac{dh}{dz} = 5.83\text{E-08 cm/sec}$$

The Darcy flux is estimated as 5.83E-08 cm/sec or 8.58E-07 gpm/ft^2. Using the previously stated assumptions and a Darcy flux of 5.83E-08 cm/sec and assuming an effective porosity of 0.10 (η), the seepage velocity (v) can be obtained from the Darcy flux using the following relationship:

$$v = \frac{q}{\eta} = 5.83E-07\,cm\,/\,sec$$

The seepage velocity represents the advective transport rate of nonreactive contaminants. The estimated seepage velocity of 5.83E-07 cm/sec demonstrates the relatively slow vertical movement of groundwater in the LHSU. At the rate of 5.83E-07 cm/sec, a conservative contaminant will only have traveled 9 meters through the LHSU in approximately 50 years.

6.4.2 Groundwater Geochemistry

The major-ion chemistry and environmental isotope compositions of the upper and lower hydrostratigraphic units were evaluated in the Groundwater Geochemistry Report (EG&G, 1995b). The results of these analyses were used as supplemental information for evaluating the interaction between the UHSU and LHSU. Findings from the Groundwater Geochemistry Report are summarized in this section.

The major-ion chemistry of the hydrostratigraphic units was evaluated using Stiff and Piper trilinear diagrams. Stiff diagrams show that the major-ion chemistry of the UHSU groundwater is distinctly different than that of the LHSU groundwater. Other than some wells within IHSSs, the Stiff diagrams of various geologic units within the UHSU consistently show similar ion contents and can generally be described as a calcium-bicarbonate type. Conversely, Stiff diagrams of LHSU groundwater indicate a sodium-bicarbonate to sodium-sulfate water type. LHSU groundwater also displayed wider variations in ionic content than UHSU groundwater. These factors indicate that the ion chemistry of the UHSU and LHSU are significantly different (EG&G, 1995b).

Piper trilinear diagrams also displayed significant differences in major ion chemistry between the UHSU and LHSU. In the Rock Creek area, Piper diagrams indicate a distinct difference in the cation content of groundwater of the two hydrostratigraphic units. The LHSU groundwater generally has a higher sodium content and a wider variation in cation content than the UHSU. In the OU4 area, the major-ion chemistry is

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slightly reversed. The UHSU groundwater geochemistry is more variable; however, this may be related to contamination sources in the Industrial Area (EG&G, 1995b).

Environmental isotope compositions of oxygen (^{18}O) and hydrogen (deuterium [D] and tritium [^{3}H]) are useful indicators for determining the degree of hydraulic interaction between the upper and lower hydrostratigraphic units. The isotope compositions of $\delta^{18}O$ and δD are expressed as parts per thousand ($^{o}/_{oo}$, per mil) difference from the Standard Mean Ocean Water (SMOW) given by the following expression:

$$\delta D \text{‰} = \{(D/^{3}H_{(sample)} - D/^{3}H_{(SMOW)})/D/^{3}H_{(SMOW)}\} * 10^{3}$$

$$\delta^{18}O \text{‰} = \{(^{18}O/^{16}O_{(sample)} - {}^{18}O/^{16}O_{(SMOW)})/^{18}O/^{16}O_{(SMOW)}\} * 10^{3}$$

Histograms displaying $\delta^{18}O$ values show distinct variations in the range of values and central tendency of $\delta^{18}O$ distributions between the UHSU and LHSU. The $\delta^{18}O$ values in the UHSU range from -16.5 to -10.3 in surficial deposits groundwater and -19.2 to -10.1 in weathered bedrock groundwater. The range of $\delta^{18}O$ (-15.5 to -10.5) for the LHSU groundwater is similar to the range of $\delta^{18}O$ values in surficial deposits groundwater but has much less variation than weathered bedrock groundwater. However, there is a shift in increased ^{18}O and D contents with depth within the LHSU, thereby indicating a recharge source other than the UHSU groundwater.

Tritium is a useful indicator for determining the relative ages of groundwater flow systems. The majority of tritium in the natural environment is attributed to atmospheric fallout from nuclear weapons testing. Because the half-life of tritium is 12.43 years, tritium concentrations in groundwater are indicators of the age of natural waters. The expected tritium content of water infiltrating into the groundwater system prior to nuclear testing is typically less than three TUs.

The tritium content of UHSU groundwater ranges from 10 to 50 TUs. Tritium content in the UHSU is highly variable at shallow depths due to mixing with surface water recharge. This variation in tritium content decreases with depth in the UHSU. In contrast, the majority of the tritium samples in the LHSU were below the detection limit. These results suggest that LHSU groundwater is older than UHSU groundwater and may originate from different sources of recharge (EG&G, 1995b).

Generally, the isotope data suggests that the LHSU and UHSU are distinct groundwater flow systems that are not in direct hydraulic connection. At deeper depths there is a slight positive shift in $\delta^{18}O$ and δD contents suggesting another source of recharge that is indicated by the tritium contents to be much older than the UHSU groundwater. The low tritium concentrations in the LHSU also indicate that the age of this groundwater system is greater than 40 years (EG&G, 1995b). The isotope data coincide with the hydrograph analysis (refer to Section 6.4.11) which suggests that the LHSU and UHSU

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are generally two separate groundwater flow systems with little or insignificant amount of hydraulic connection between the two units.

However, hydraulic connection between the UHSU and LHSU may occur in isolated areas. Despite the positive shift in $\delta^{18}O$ and δD content and lower tritium concentrations in the LHSU groundwater, VOCs detected in the LHSU indicate potential mixing of upper and lower HSU groundwaters in some areas at Rocky Flats (EG&G, 1994a). The presence of trichloroethylene (TCE) in LHSU groundwater at OU2 (well 23193) (DOE, 1993b) and other VOCs at well clusters 6 and 53 may indicate limited hydraulic connection between the upper and lower hydrostratigraphic units in some areas. It has been postulated, however, that some of these occurrences of VOCs may have resulted from cross-contamination during well installation (DOE, 1994c).

6.4.3 Preferential Groundwater Flow Through Secondary Permeability

Secondary permeability through interconnected high-angle fractures and fault zones in the unweathered bedrock may enhance localized hydraulic interactions between the upper and lower HSU. In OU2, open continuous fractures were observed to a depth of approximately 60 feet. Iron-oxide staining along the fracture planes confirms the downward movement of groundwater. Acoustic televiewer logs (of well 21593) showed that the degree of fracturing began to decrease approximately 100 feet below ground surface (DOE, 1993b).

Postulated fault zones within the bedrock were identified in the Geologic Characterization Report (EG&G, 1995a). Inferred bedrock faults in or near the Industrial Area may have an impact on preferential groundwater flow. A north-south-trending fault is inferred below the Solar Evaporation Ponds in OU4. This fault is truncated on the north and south by two prominent northeast-trending faults. The northeast-trending fault to the north of OU4 is inferred beneath the Industrial Area and OU7. This fault also truncates a minor north-northeast-trending fault near OU10. A second northeast-trending fault to the south of the Industrial Area is inferred under OUs 1 and 2. Brecciated zones within the bedrock along the traces of these postulated faults were noted during drilling investigations (F. Grigsby, personal communication, 1994). Well cluster 6 exhibits a hydraulic connection between the upper and lower hydrostratigraphic units and is near one of these faults. This may suggest that these fault zones are enhancing the permeability of the bedrock, effectively creating a preferential flowpath between the upper and lower hydrostratigraphic units (EG&G, 1995a).

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6.4.4 Conclusions

Well-cluster hydrographs and geochemical data demonstrate a minimal or insignificant amount of hydraulic interaction between the UHSU and LHSU. However, in some areas the LHSU only appears to be in direct hydraulic connection with the overlying UHSU at depths of less than 50 feet below the bedrock unconformity. There is evidence of hydraulic connection between the hydrostratigraphic units in OU2 where LHSU sandstones subcrop or are within close vertical proximity of the UHSU. However, the geometry of these LHSU sandstone units has been characterized as being laterally discontinuous in nature and, therefore, these sandstone units are unlikely to represent pathways for offsite contaminant migration (EG&G, 1995a). Generally, flow in the LHSU is downward on the ridge tops. However, some upward components of flow are present in stream valleys. The relatively low saturated hydraulic conductivity of the LHSU (e.g., 10^{-7} cm/sec horizontal saturated hydraulic conductivity and 10^{-8} cm/sec vertical saturated hydraulic conductivity) suggests that the LHSU generally acts as an effective barrier to downward flow.

The groundwater geochemistry of the two hydrostratigraphic units is distinctly different. The UHSU groundwater is generally classified as a calcium-bicarbonate-type water compared to the sodium-bicarbonate to sodium-sulfate classification for LHSU groundwater. The relative increase in $\delta^{18}O$ and δD with depth and low tritium concentrations in the LHSU suggest that the hydraulic interaction between the UHSU and LHSU is generally insignificant and at the most very limited (EG&G, 1995b).

The geochemistry and hydraulic properties of the upper and lower hydrostratigraphic units indicate that the interactions between the two units are minimal. However, in some areas the limited presence of low concentrations of VOCs in the LHSU demonstrates that some movement of groundwater may occur between the two units. Interconnected fracturing and fault zones in bedrock may increase permeability, thereby enhancing the hydraulic interactions between the two units. These interconnected fractured zones have been observed in OU2. Potential bedrock faults have also been inferred under the Industrial Area and in OUs 1, 2, 4, and 7 (EG&G, 1995a).

6.5 Surface-Water/Groundwater Interactions

This section describes surface-water/groundwater interactions at the Rocky Flats site. Potentiometric-surface maps, a seep location map, stream/well-cluster hydrographs, longitudinal profiles, pond dam design, dam piezometer data, stream-gaging data, Woman and Walnut Creek water-balance studies, and East Spray Field data were used to characterize surface-water/groundwater interactions at Rocky Flats.

Surface water at Rocky Flats occurs as streams, seeps, ponds, ditches, and lakes. A description of surface-water features at Rocky Flats is presented in Section 3.3.1.

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Shallow groundwater at Rocky Flats exists within the UHSU, which is described in Section 6.2. There is considerable interaction between surface water and groundwater at Rocky Flats (EG&G, 1991c). Surface-water seepage into shallow groundwater occurs at streams, seeps, ponds, ditches, and lakes. Shallow groundwater discharges to the surface at seeps and within drainages. All of these interactions vary spatially and temporally.

Due to the limited nature of data describing surface-water/groundwater interactions at the Rocky Flats site, two sources of information were used to develop a conceptual understanding of these interactions. The Woman Creek Infiltration/Exfiltration Study (EG&G, 1993h) and the Walnut Creek Water Balance (EG&G, 1994d) were used to develop a conceptual understanding of the spatial and temporal patterns of surface-water/groundwater interaction at Rocky Flats. Other data from hydrographs, seeps, and dam piezometers were then used to confirm the conceptual model of surface-water/groundwater interactions developed from the two studies.

6.5.1 Woman Creek Infiltration/Exfiltration Study

Woman Creek has been the focus of most of the investigative research on the interaction of surface water (stream flow) and groundwater at the Rocky Flats site. Stream flow measurements were collected with Cutthroat flumes at 29 stations along Woman Creek on a monthly basis from August 1992 to September 1993 (Fedors and Warner, 1993). The results were used to identify gaining and losing segments of the stream. A stream or reach of a stream that is increasing in flow volume as the result of inflow from groundwater is considered gaining or effluent. Conversely, a stream or reach of a stream that is losing water by seepage into the ground is considered losing or influent. Segments of Woman Creek were placed into one of the following four general classifications: creek gains year-round, creek gains during spring (December through March or April) and loses during the rest of the year, creek losses year-round, or creek experiences a gain for two months or less and losses during the rest of the year (EG&G, 1993c). The stream segments and their corresponding classifications are presented on Figure 6-22.

In the upper Woman Creek drainage near the western boundary of the Rocky Flats site, several segments of the stream gain water year-round. These segments are between stations 5-6, 6-7, and 9-10 and upstream of station 14 (Figure 6-22). Perennial seeps and associated high groundwater levels in the area are probably the groundwater source for these gaining stream segments. The largest of these perennial seeps is Antelope Springs. Stable flow from Antelope Springs implies that it is either a discharge point for a regional flow system or that there is a consistent recharge source to the aquifer. Potential upgradient sources of recharge to the UHSU include Rocky Flats Lake and the South Boulder Diversion Canal, both of which may lose water to the groundwater

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through seepage (DOE, 1992b). Isotope chemistry indicates that Rocky Flats Lake is a recharge source to the UHSU and Antelope Springs. Heavy-isotope-enriched water at Antelope Springs suggests that the water ultimately originates, at least in part, from Rocky Flats Lake (EG&G, 1994d), which is enriched in heavy isotopes due to evaporative fractionation.

Stream segments between stations 1-2, 2-3, 3-4, 4-8, 8-9, and 11-12, on Woman Creek in the western portion of the Rocky Flats site gain in the spring and lose during the rest of the year. Groundwater elevations within the unconsolidated materials rise in the spring in response to high recharge rates. These stream segments probably gain water from the seasonally high water table and from ephemeral seeps. With reduced recharge in the late summer and fall and lowered water-table elevations, discharge from ephemeral seeps ceases, and gaining segments of Woman Creek lose water to the valley-fill alluvium as the water table drops below the bottom of the channel.

The eastern portion of Woman Creek at Rocky Flats generally loses water to groundwater year-round or for all but two months out of the year. These influent conditions occur along the stream segments between stations 10-11, 12-16, 16-17, C1-18, 20-21, 21-22, 22-23, and 23-24 (Figure 6-22). Near Ponds C-1 and C-2, groundwater within the valley-fill alluvium is typically 5 to 7 feet below ground surface (DOE, 1992b). Within the Woman Creek drainage, unsaturated conditions are typical within the unconsolidated material downstream from Pond C-2 following the high-water stage in the spring (Plate 3). Longitudinal profile D'-D" (Plate 13) illustrates the unsaturated nature of the unconsolidated material below Pond C-2 during the fourth quarter of 1993. The depth to groundwater and unsaturated conditions within unconsolidated materials result in the general influent nature of the eastern portions of Woman Creek.

There are, however, several short segments of Woman Creek, east of the confluence with the Antelope Springs drainage, that gain either year-round or during the spring. These stream segments are between stations 17-C1, 18-19, and 19-20 (Figure 6-22). A thicker section of the valley-fill alluvium is saturated in the spring when recharge to the alluvium is high within these sections (Plate 4). The short, seasonally gaining segments of Woman Creek could result from the seasonal increase in saturated thickness at these locations. One short segment of Woman Creek east of the confluence with the Antelope Springs drainage gains year-round (Segment 18-19). This may be due to small paleochannels incised on the bedrock surface along the hillslopes within the Woman Creek drainage (EG&G, 1995a, Plate 4-3). These bedrock paleochannels may preferentially collect and move groundwater downslope to a discharge point corresponding to this gaining segment of Woman Creek. The effect of bedrock paleochannels on groundwater flow is discussed in Sections 6.2.3.2 and 6.2.3.3.

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Another surface-water feature within the Woman Creek drainage that may interact with shallow groundwater is the SID. The SID was constructed in 1980 to intercept surface runoff from the Industrial Area. Flow in the SID is intermittent and generally occurs only following precipitation events or snowmelt (DOE, 1992b). Because the SID is engineered with a series of riprap-lined plunge pools instead of a continuous grade, it is difficult to determine whether various segments of the ditch are gaining or losing. The western portion of the SID may gain or lose water depending on local groundwater elevations; however, the eastern portion of the SID appears to lose water as the plunge pools along this reach are almost always dry (EG&G, 1992e).

The results of the Woman Creek study generally indicate that Woman Creek gains water from the groundwater, particularly during the wet spring months, from the western Rocky Flats site boundary to its confluence with the Antelope Springs drainage. Downgradient from the Antelope Springs drainage to the eastern Rocky Flats site boundary, Woman Creek generally loses water through seepage into the valley-fill alluvium. The spatial distribution of gaining and losing sections of Woman Creek is controlled by the location of groundwater sources from seeps, springs, or bedrock paleochannels and the relative elevation of groundwater to the channel bottom. This is confirmed by the generally influent nature of Woman Creek in the eastern portion of Rocky Flats where these sources are not present and the thickness of unsaturated surficial deposits increases. The ephemeral nature of stream flow at Rocky Flats is due to the fact that most streams lose flow to groundwater during most of the year except in localized areas near springs, seeps, and other groundwater discharges such as hillside bedrock paleochannels.

6.5.2 Walnut Creek Water Balance

Of the three major drainages at Rocky Flats, Walnut Creek receives most of the surface runoff from the Industrial Area (EG&G, 1992d). As a result, surface water in the Walnut Creek drainage is heavily managed and flow is controlled and influenced by a series of detention ponds and various interceptor and diversion ditches. In addition, effluent from the Waste Water Treatment Plant (WWTP) is discharged into the drainage at Pond B-3. Surface-water features within Walnut Creek are discussed in Section 3.3.1. Discharge volumes from seven surface-water gaging stations in the Walnut Creek drainage were measured for eight periods of continuous record during water year 1993. The seven stream gaging stations were GS03, GS08, GS09, GS10, GS11, GS12, and GS13. These stations are posted on Figure 6-23. These data were used to calculate the contribution of flow to Walnut Creek from North Walnut Creek, South Walnut Creek, and the WWTP and to determine the percent gain/loss of surface-water flow for the basin and for individual segments within the basin.

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Definite gain/loss patterns were calculated for only one of the measured segments of Walnut Creek. Data indicated that the segment of Walnut Creek from Pond A-4 (GS11) to the eastern site boundary (GS03) loses water to the valley-fill alluvium throughout the year. The calculated loss through this segment ranges from approximately 8 to 41 percent of the surface-water flow within the stream. The gain/loss pattern of other measured segments within Walnut Creek could not be positively explained, possibly due to inaccurate pond-level measurement and discharge data. However, fairly consistent baseflow in the western portion of North Walnut Creek at station GS13 is due to groundwater seepage (EG&G, 1994d). Although stream gaging data on Walnut Creek are not sufficiently accurate to allow for definite determination of gain/loss patterns, general spatial and temporal trends are discernible. Effluent stream conditions are dominant along western portions of the drainage in the spring, and the eastern segment of the drainage is consistently influent.

6.5.3 Comparison of Stream-Gaging Data and Alluvial-Well Hydrographs

Thirteen primary stream-gaging stations (GS01–GS13) are used to monitor stream flow at Rocky Flats (Figure 6-23). Mean values for daily discharge values are generated from stage data collected at each of the stations. Surficial-deposit wells located near 11 of the stream-gaging stations were evaluated with stream-stage data to characterize gaining and losing stream segments. Elevations of the stream-gaging stations have not been determined, and the associated surficial wells are commonly some distance away from the stream-gaging station. The lack of accurate stage data and the inaccuracies of stage measurement allow only the identification of general trends in surface-water/groundwater interactions using these data. Locations of surficial-deposit wells are included on Plate 2, and the combined stream stage/surficial-deposit well hydrographs are presented in Appendix F.

All of the stream-gaging stations reflect the ephemeral nature of stream flow in the drainages at Rocky Flats. When the effect of pond and Industrial Area discharges are removed, all of the stations exhibit similar seasonal discharge patterns. Flow is generally minimal or zero during much of the year. The majority of the flow occurs during snowmelt and precipitation events in the spring. Stream discharge in the spring is in response to increased precipitation and recharge, rising groundwater levels, ephemeral seep discharge, and saturated soils (EG&G, 1993b).

Surficial deposit wells B402689 and 5386 are located near stream gaging stations GS05 and GS06, respectively, on the western boundary of the Rocky Flats site in tributaries of Woman Creek (Figure 6-23). Groundwater levels within these wells correspond to seasonal fluctuations in stream discharge. Water levels within the surficial deposits at these wells are highest during the spring months and become unsaturated in the summer and fall (Appendix C). High groundwater levels in the spring rise to within

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1.4 and 3 feet of the ground surface at wells B402689 and 5386, respectively. The majority of stream flow at stream-gaging stations GS05 and GS06 occurs during this high-water period in the spring. Discharge volumes at these stations is low or zero during much of the rest of the year. Potentiometric and stream-stage data suggest that these stream segments may gain water during the spring but lose water, if and when flow occurs, during most of the year. This general interaction is supported by the Woman Creek Infiltration/Exfiltration Study (Section 6.5.1) (EG&G, 1993h).

Stream-gaging stations GS08, GS09, GS11, and GS12 are located on the principal outlets below Ponds B-5, B-4, A-4 and A-3, respectively (Figure 6-23), in the Walnut Creek Drainage. Station GS08 is always dry because no water is presently discharged downstream from Pond B-5. Stream flow at station GS09 is heavily influenced by discharge from the sewage treatment plant and Industrial Area footing drains. Baseflow at station GS09 is maintained year-round by the sewage treatment plant operations. Stations GS11 and GS12 only record flow when water is discharged from Ponds A-4 and A-3, respectively. The absence of stream flow below these pond embankments except during discharge periods supports the hypothesis that the dams are generally effective in impeding flow and that these sections are not gaining flow from groundwater.

Four stream gaging stations are located along the eastern and northern boundaries of Rocky Flats where major stream drainages leave the site. These stations are GS01, GS02, GS03, and GS04 and are respectively located on Woman Creek, Mower Ditch, Walnut Creek, and Rock Creek (Figure 6-23). The majority of flow at all of these stations results from snowmelt and precipitation in the spring. These stations are generally dry during the rest of the year. Surficial deposit wells 0186 and 41491 are located near station GS01 in Woman Creek. Groundwater levels within the alluvium at these wells fluctuates seasonally with high water levels occurring in the spring and unsaturated conditions occurring in the summer and fall (Appendix C). During the high-water stage in the spring, groundwater within the alluvium at these wells is greater than 4 feet below the ground surface, and it is likely that this stream segment loses water through seepage into the alluvium. The influent conditions along the eastern portions of the drainages at Rocky Flats is supported by the Woman Creek Infiltration/Exfiltration Study (EG&G, 1993h) and the Walnut Creek water balance (EG&G, 1994d).

Well 40791 is located 500 feet upstream of stream gaging station GS02 on Mower Ditch. The surficial deposits at this well are always unsaturated. The absence of shallow groundwater within the alluvium indicates that this stream segment loses water through seepage into the alluvium.

Wells 0486 and 41691 are located on Walnut Creek near stream gaging station GS03. The alluvium at these two wells is typically partially saturated with seasonal fluctuation in groundwater elevation. Maximum groundwater elevations occur in the spring (see single-well hydrographs, Appendix C). High water levels within these two wells are approximately 4 feet below the ground surface, indicating a downward flow into surficial deposits and a losing stream segment.

Alluvial well B202589 is located near stream gaging station GS04 on Rock Creek (Figure 6-23). Only large storm or snowmelt events occurring on previously saturated soils produce measurable runoff at this station (EG&G, 1993b). Some saturated alluvium exists at well B202589 year-round and water levels display limited seasonal fluctuations (Appendix C). High water elevations in this well are within 1.5 feet of the ground surface. The general lack of stream flow and the depth to groundwater suggest that the segment loses flow to groundwater when surface water is present.

The stream stage/alluvial-well hydrographs on the western boundary of the Rocky Flats site (GS05/B402689 and GS06/5386), near the drainage headwaters, suggest a seasonal change in the gain/loss status of these stream segments. These stream segments may gain water from groundwater in the spring and probably lose water to groundwater during the rest of the year. Whereas, stream stage/alluvial-well hydrographs on the eastern boundary of the Rocky Flats site (GS01/0186 and 41491, GS02/40791, GS03/0486 and 41691, and GS04/B202589) appear to lose water to the groundwater throughout most of the year. These observations are supported by the Woman Creek Infiltration/Exfiltration Study (EG&G, 1993h) as well as the Walnut Creek water balance (EG&G, 1994d).

6.5.4 Stream Profile/Hydrogeologic Cross Sections

Stream profile/hydrogeologic cross sections were constructed along No Name Gulch, North Walnut Creek, South Walnut Creek, and Woman Creek. The potentiometric surface within the unconsolidated surficial deposits during the second and fourth quarters of 1993 were plotted on each of the cross sections (Plates 17, 18, 19, and 20). The stream profile cross sections illustrate the drop in groundwater elevations from the second to the fourth quarter of the year. Higher groundwater elevations during the spring correspond to seasonal effluent conditions along localized stream segments. The cross sections also illustrate the general unsaturated nature of the unconsolidated surficial deposits during the fourth quarter of the year, particularly along the eastern portions of the streams. Lower groundwater elevations and unsaturated conditions within the unconsolidated surficial deposits during the fourth quarter correspond to the general influent or losing nature of the streams.

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6.5.5 Dam Piezometer Data

Surface-water management at the Rocky Flats site includes a series of detention ponds in the Walnut and Woman Creek drainages. All of the dams are earthen structures that are typically keyed into bedrock. Piezometers installed in the crest and toe of these structures are used to monitor water levels within the structures and to determine the stability of the dams. Pond dam design and piezometer data were qualitatively evaluated to assess seepage through the dams and to characterize surface-water/groundwater interactions associated with these structures.

Dam piezometer data are presented and evaluated in the SWD Field Report Series (EG&G, 1993i). Dam piezometer hydrographs are presented in Appendix E. All but one of the dam crest piezometers indicate a direct relationship to pond-level changes. Similarly, most of the piezometers located at the toe of the dams show direct relationships to changes in pond levels; however, they are also influenced to some degree by local groundwater (EG&G, 1993i). Toe piezometers on dams A-4 and C-2 respond to physical factors unrelated to pond levels. Water-level data for these piezometers suggest that bedrock groundwater and pond water are not hydraulically connected at these locations. However, the general positive relationship between pond levels and dam piezometers indicates a hydraulic connection between the ponds and the embankment materials.

Hydraulic conductivity values measured in the crest piezometers are relatively low (10^{-6} cm/sec to 10^{-9} cm/sec); however, the presence of water in piezometers installed at the toe of the dams indicates that some flow through or around the embankments takes place (EG&G, 1993i). Seeps identified on the downstream slopes of dams B-3 and B-5 verify that groundwater flow takes place through these embankments (EG&G, 1994a and EG&G, 1993g).

Although piezometers and seeps indicate groundwater movement through the embankments, actual flow volumes are probably small. This is due to the low hydraulic conductivities of the embankment cores and the low permeability of the bedrock. Surficial deposit wells positioned below several of the dams are unsaturated for at least a portion of the year. A water balance performed on the Landfill Pond supports the idea that minimal groundwater flow occurs through the embankment. The water balance estimated that the groundwater volume flux beneath the dam was 9.23E-07 ft^3/sec, which equates to 218 gallons per year (DOE, 1994a).

As-built construction diagrams of dams A-3, A-4, B-1, B-3, B-5, and C-2 and the Landfill Pond dam indicate that the embankment cores of these dams are keyed into bedrock; (EG&G, 1993g, and DOE 1992b and 1992c). Bedrock beneath dams A-3, A-4, and B-1 consists of consolidated claystone. Due to the low permeability of the

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claystone, it is unlikely that a large volume of groundwater seeps below these dam foundations (EG&G, 1994a). Bedrock beneath dam B-3 and the Landfill Pond dam consists of consolidated silty sandstone, siltstone, and claystone (EG&G, 1993g). The degree to which impounded surface water within these ponds migrates into bedrock groundwater has not been assessed, nor has the degree to which bedrock groundwater may migrate beneath the dams (EG&G, 1994a). Bedrock lithologies beneath dams B-5 and C-2 were not described in the as-built diagrams, but all unconsolidated material was probably removed during construction.

Groundwater-elevation data from the surficial materials near the Landfill Pond indicate that groundwater levels are consistently higher than the pond level, suggesting that surficial groundwater deposits are continuously recharging the pond. Groundwater elevations in the unconsolidated material near the Landfill Pond and surface-water elevations of the Landfill Pond have similar seasonal trends, suggesting that the two are hydraulically connected. Although the Landfill Pond appears to be continuously recharged from groundwater within the surficial deposits, water levels in a weathered bedrock well near the shoreline are consistently lower than the pond water. This indicates that the Landfill Pond may be recharging weathered bedrock near the shoreline. These data support the existence of surface-water/groundwater interaction in association with the pond and provide evidence as to the complexity of these interactions (DOE, 1994a).

6.5.6 Seeps

A seep location map was generated for the Rocky Flats site utilizing previously compiled seep maps, aerial photography, and field reconnaissance (Plate 9). Seep distribution and occurrence is strongly controlled by geology. Seeps at Rocky Flats are common along the eastern extent of the Rocky Flats Alluvium. The contrasting hydraulic conductivities of the permeable unconsolidated surficial deposits and the relatively impermeable underlying bedrock produces lateral groundwater movement along this contact. Much of the groundwater within the unconsolidated surficial deposits discharges at seeps along the upper margin of the drainages where the contact between the Rocky Flats Alluvium and the underlying claystone subcrops (EG&G, 1994a). Lateral groundwater movement at the surficial-deposit/bedrock contact may also flow preferentially along paleochannels within the surface of the bedrock. Some seeps are located where paleochannels intersect the drainage slopes (DOE, 1994f and DOE, 1994g). Most of the seeps along the eastern extent of the Rocky Flats Alluvium occur on the north side of the pediment ridges. This general pattern of seep occurrence results primarily from bedrock control of groundwater flow within the Rocky Flats Alluvium. The bedrock surface at Rocky Flats dips slightly to the northeast resulting in a northeastern component of groundwater flow within the Rocky Flats Alluvium. Bedrock paleochannels also generally trend to the northeast. Groundwater flow within

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the Rocky Flats Alluvium follows the northeast trend of the bedrock surface toward seeps on the north side of the pediment ridges.

Most of the seeps at Rocky Flats are ephemeral in nature and only discharge in the spring. Ephemeral seeps at Rocky Flats follow a seasonal trend similar to water levels in the unconsolidated surficial deposits. Seep flow at Rocky Flats is greatest during the high-water period in the spring. Reduced recharge to the unconsolidated material in the summer and fall causes water levels to drop, and seep activity is correspondingly reduced. Many of the seep areas stop discharging in the summer and fall.

Seep discharge does not always result in surface-water flow but may occur through transpiration (Section 3.2.1). Distinctive plant communities are associated with wetlands at Rocky Flats and are useful in delineating wetland and seep areas (U.S. Army Corps of Engineers, 1994). Seasonal fluctuations in transpiration rates affect surficial seep discharge at RFETS. High transpiration rates in the summer reduce or eliminate surface flow at some seeps, and surficial flow resumes or increases at these seeps in the fall when plants become dormant and water is no longer transpired by the vegetation.

In the OU2 area, seeps along the edge of the drainages are associated with a thick sandstone unit (Arapahoe Formation sandstone) that subcrops beneath the Rocky Flats Alluvium. The Arapahoe Formation sandstone is recharged from the overlying surficial-deposits. Groundwater within the Arapahoe Formation sandstone flows toward the South Walnut Creek and Woman Creek drainages and discharges at seeps on hillsides where the sandstone subcrops beneath the colluvium (EG&G, 1994a). Another seep within OU2 along South Walnut Creek is caused by the discharge of groundwater from the northeast end of a bedrock paleochannel. At this location, the bedrock channel acts as a conduit of groundwater to the hillside (EG&G, 1994a). Seep activity within OU2 is ephemeral and discharge occurs in the spring.

Within OU1, seeps have been noted near the head region of slumps that exist on the northern hillside within the Woman Creek drainage. This suggests that groundwater may be flowing from depressions in the bedrock surface near the head region of slumps. Other seeps appear to be related to slump margins (DOE, 1994g). Seep activity is ephemeral and discharge is associated with high groundwater levels in the spring.

Within No Name Gulch in OU7, groundwater and leachate within surficial deposits and landfill materials flow toward the center of the buried drainage and eventually discharge at a seep located at the toe of the landfill. The seep is perennial and discharges into the Landfill Pond (DOE, 1994a).

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Seeps are an important surface-water feature within OU4. Several seeps have been observed near the surficial deposit/bedrock contact on the hillside north of the Solar Evaporation Ponds since the original bentonite-lined pond was installed. Additional seeps were noted along the northern hillside after the construction of the present lined Solar Evaporation Ponds. These seeps are associated with discharge sumps at the end of drainage tiles installed beneath the Solar Evaporation Ponds. Flow rates and volumes from these seeps are not available but the seeps are ephemeral in nature. Some component of flow from these seeps probably originates from the Solar Evaporation Ponds as indicated by elevated nitrate/nitrite concentrations (DOE, 1994c).

Antelope Springs is a large perennial seep area located along the Rocky Flats Alluvium/bedrock contact at the western headwaters of a tributary to Woman Creek (Plate 9). Discharge at Antelope Springs is fairly consistent. Tritium data indicate that Rocky Flats Lake is a source of recharge to the Rocky Flats Alluvium that eventually discharges at Antelope Springs.

Other seep areas on drainage hillsides throughout the site may be due to thinning of the colluvial materials. These seeps form where groundwater is flowing within the colluvium on top of the underlying impermeable bedrock and the colluvium thins to the point where the potentiometric surface intersects the ground surface. Ephemeral seeps of this nature are located on hillsides within OU1 and OU2 (DOE, 1992d and 1993b).

6.5.7 South Spray Area

The South Area of the East Spray Field (OU2) received sewage treatment plant effluent from Pond C-3 from the early 1980s to 1990. The South Spray Area was located on the ridge between South Walnut Creek and Woman Creek, south of the East Access Road. Water was applied to the fields through spray irrigation. It is estimated that as much as 20 million gallons of water per year were disposed of at the East Spray Fields. Spray irrigation was initiated as an action to achieve zero offsite discharge of sanitary effluent from the Rocky Flats site. The spray operation was intended to return the effluent to the hydrologic system through evaporation (DOE, 1992c).

A water balance performed on the South Spray Area determined that a large portion of the applied water did not evaporate but was lost to runoff and infiltration (Koffer, 1989). The study indicated that during warm months when the ground was thawed about 35 percent of the sprayed water infiltrated into and recharged the shallow water table. The large volume of recharge to the alluvium affected local water-table elevations. Three alluvial wells (2787, 3287, and 4186) located near the western end of the South Spray Area clearly show the effects of spray irrigation on the water table. Hydrographs from these three wells (Appendix C) show that prior to 1990, during spray irrigation operations, a saturated thickness of 10 feet was common within the alluvium.

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Following the end of spray irrigation in 1990, water-table elevations rapidly dropped, and the alluvium is now generally unsaturated.

In the 1980s when the South Spray Area was in operation and a portion of the surficial deposits were saturated, an ephemeral seep along the upper edge of the Woman Creek drainage appears to have been a major discharge area for this alluvial groundwater (EG&G, 1994a). Since spray irrigation was discontinued, the surficial deposits have become unsaturated, and discharge from the seep has ceased.

6.5.8 Conclusions

Seasonal fluctuations in precipitation, recharge, groundwater levels, and stream and ditch flow are reflected in surface-water/groundwater interactions at Rocky Flats. Effluent conditions are dominant in the spring along localized stream segments and influent conditions are common in the late summer and fall along most stream reaches. Effluent conditions within the drainages are more common along western stream segments of the site and influent conditions are dominant along eastern stream segments of the site.

Stream-stage and water-balance data from Woman and Walnut Creeks were used to describe surface-water/groundwater interactions at the Rocky Flats site. The effluent or influent nature of various stream segments was described using these data. The western and central portions of drainages at the site generally exhibit gaining or effluent conditions during the spring, especially in locations where groundwater sources were available in the form of springs, seeps, or bedrock paleochannels. The eastern portions of these drainages on the Rocky Flats site are dominantly influent or losing.

Groundwater movement within the drainages at Rocky Flats is modified by the pond dams. Most of the surface-water/groundwater interactions associated with these impoundments occur upstream of the dam structures as they appear to significantly impede groundwater movement downstream.

The geology at Rocky Flats exerts strong controls on seep activity and location. The majority of seep activity at Rocky Flats occurs on hillslopes at the contact between alluvium and bedrock along the eastern erosional edge of the Rocky Flats Alluvium and is ephemeral in nature.

Past spray-evaporation activities in the South Spray Area of the East Spray Field interacted with shallow groundwater in the unconsolidated material beneath the spray field. Groundwater levels were elevated and an associated seep was active during the operation of the field. Since the spray operation was discontinued, the unconsolidated materials beneath the field have become unsaturated, and the seep activity has ceased.

Table 6-1
Estimated Quantity of Groundwater Beneath the Rocky Flats Site

Hydrostratigraphic Unit	Area (acre)	Average Thickness (ft)	Average Saturated Thickness (ft)	Porosity[a] (%)	Water in Storage (acre-ft)	Water in Storage (gals x 10^9)
Alluvium and Valley-Fill	6,470	(b)	10[c]	30	19,400	6.3
Arapahoe Formation	4,970	35[d]	35	30	52,200	17.0
Laramie/Fox Hills	6,350	200	120	30	228,600	74.5
Total					**300,200**	**97.8**

(a) Assumed value based on data presented by Robson (1987)

(b) Not estimated

(c) Estimated from the difference between alluvial and valley-fill groundwater elevation and bedrock elevation throughout the Rocky Flats site.

(d) Thickness of all Arapahoe Formation siltstones and sandstones. This does not include claystone which is assumed to have no significant recoverable water. This reflects a composite thickness of sandstones which may contain recoverable water.

Source: EG&G, 1991c

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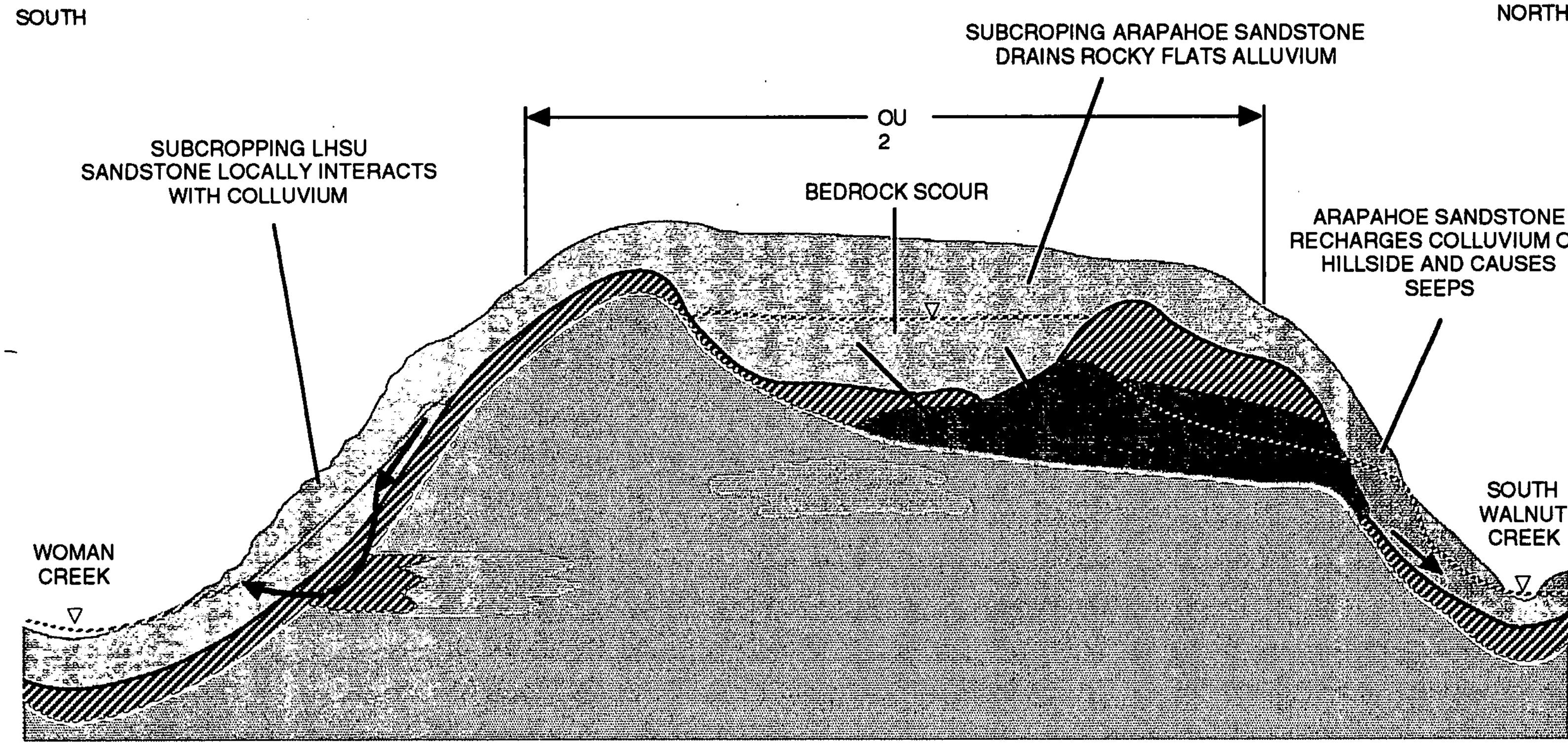

EXPLANATION

(Qrf) ROCKY FLATS ALLUVIUM		GROUND WATER FLOW DIRECTION
(Qc) COLLUVIUM		CONCEPTUAL UHSU/LHSU BOUNDARY
UNWEATHERED CLAYSTONE/ SILTSTONE BEDROCK		WATER TABLE
WEATHERED BEDROCK		
WEATHERED ARAPAHOE #1 SANDSTONE BEDROCK		
LHSU UNWEATHERED SANDSTONE BEDROCK		

DRAFT OU2 PHASE II RFI/RI

EG&G ROCKY FLATS
Rocky Flats Site, Golden, Colorado

Schematic Cross Section of Hydrostratigraphy at OU2

April 1995 | Figure 6-1

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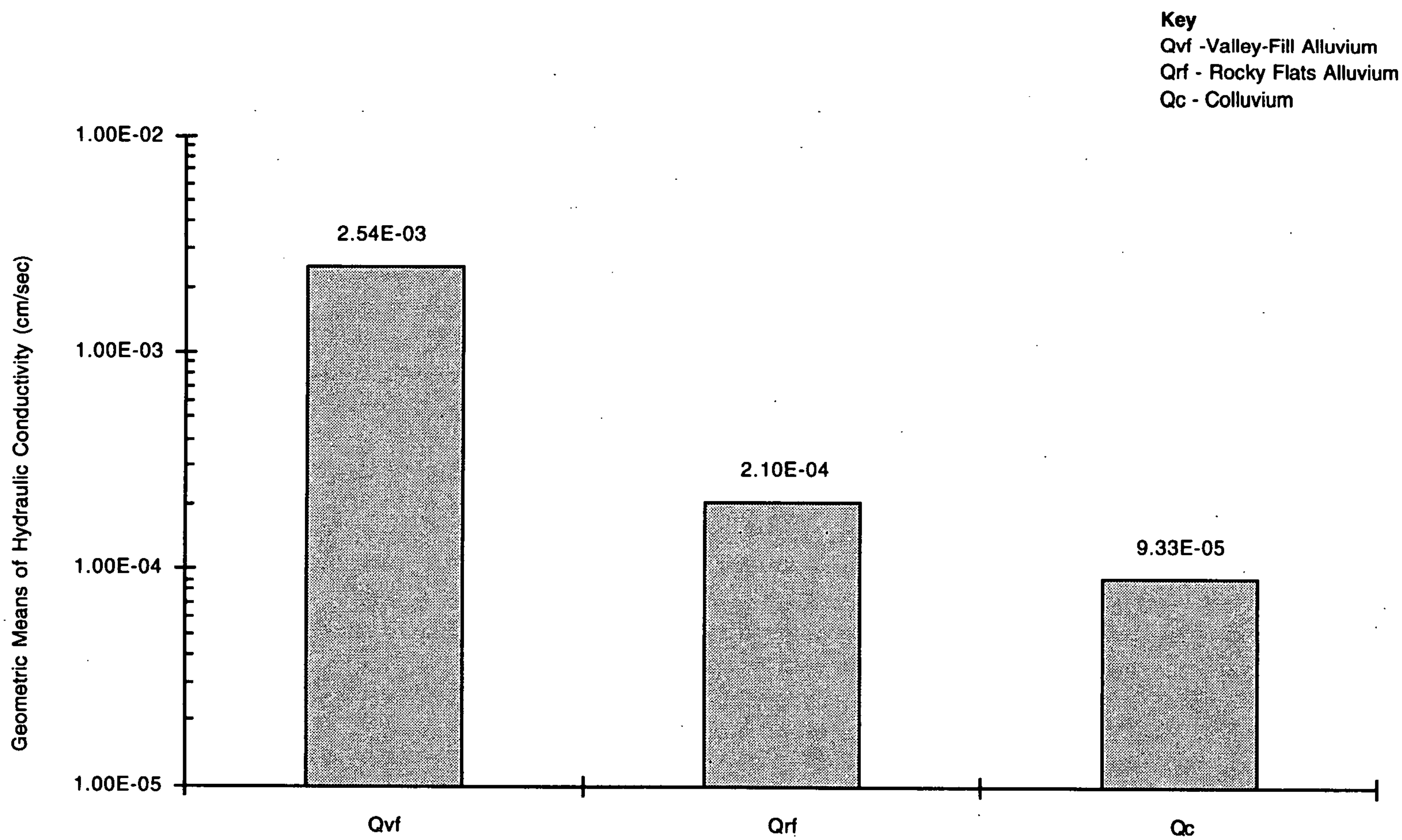

EG&G ROCKY FLATS

Rocky Flats Site, Golden, Colorado

Hydraulic Conductivity of Unconsolidated Surficial Deposits at the Rocky Flats Site

Hydrogeologic Characterization Report

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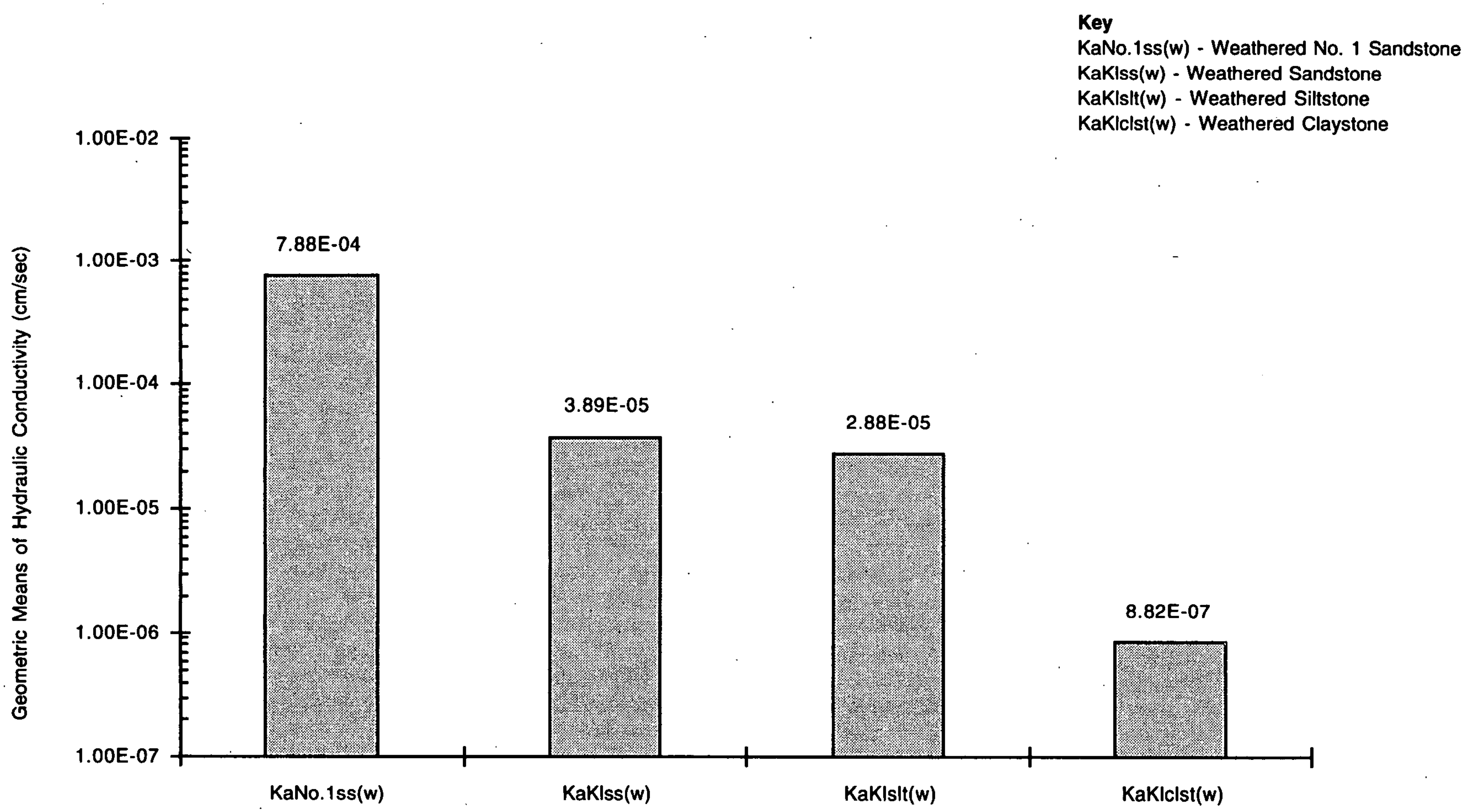

EG&G ROCKY FLATS

Rocky Flats Site, Golden, Colorado

Hydraulic Conductivity of Weathered Bedrock Units at the Rocky Flats Site

Hydrogeologic Characterization Report

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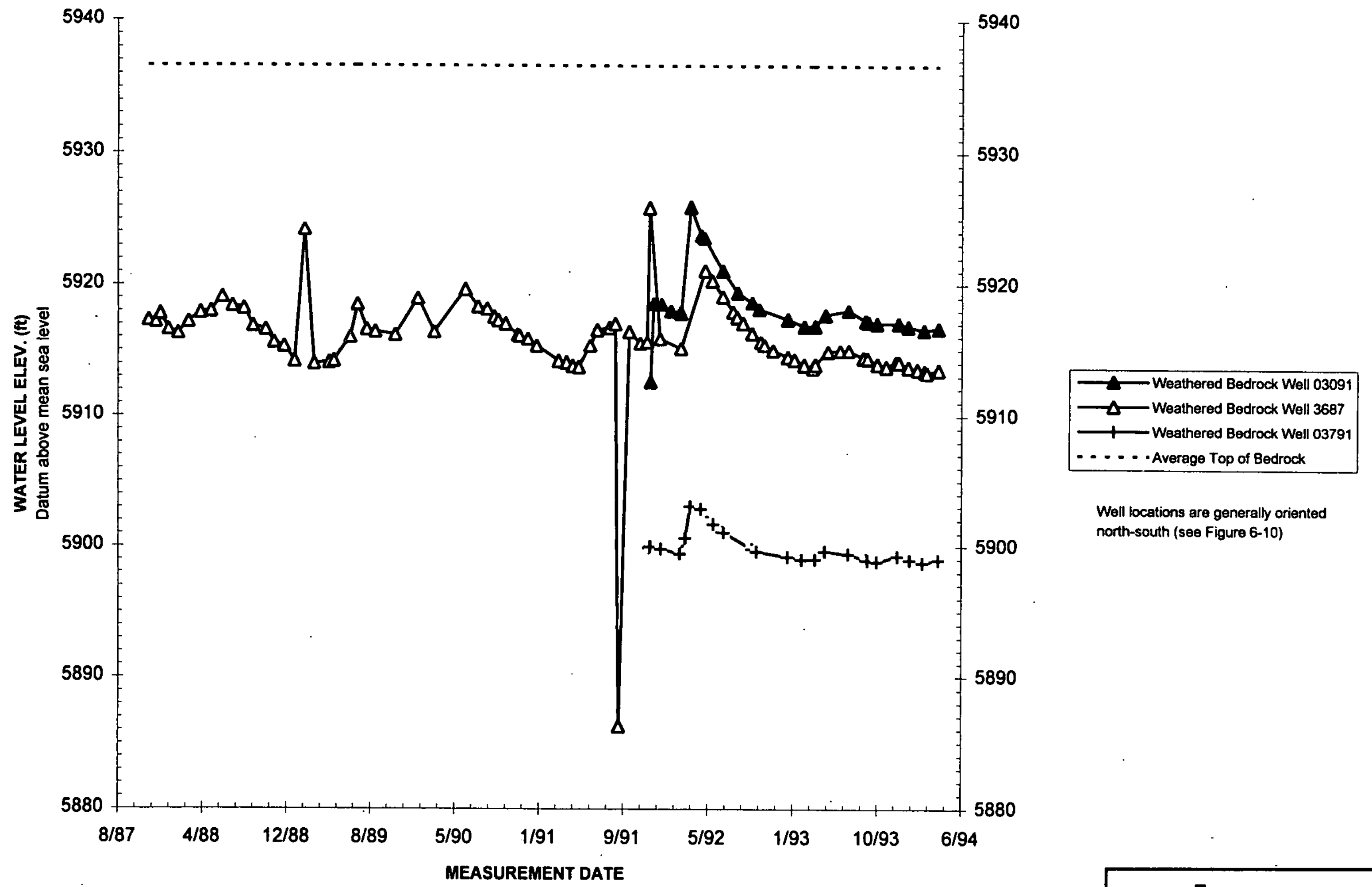

EG&G ROCKY FLATS

Rocky Flats Site, Golden, Colorado

Hydrograph of Arapahoe Sandstone Wells

Hydrogeologic Characterization Report

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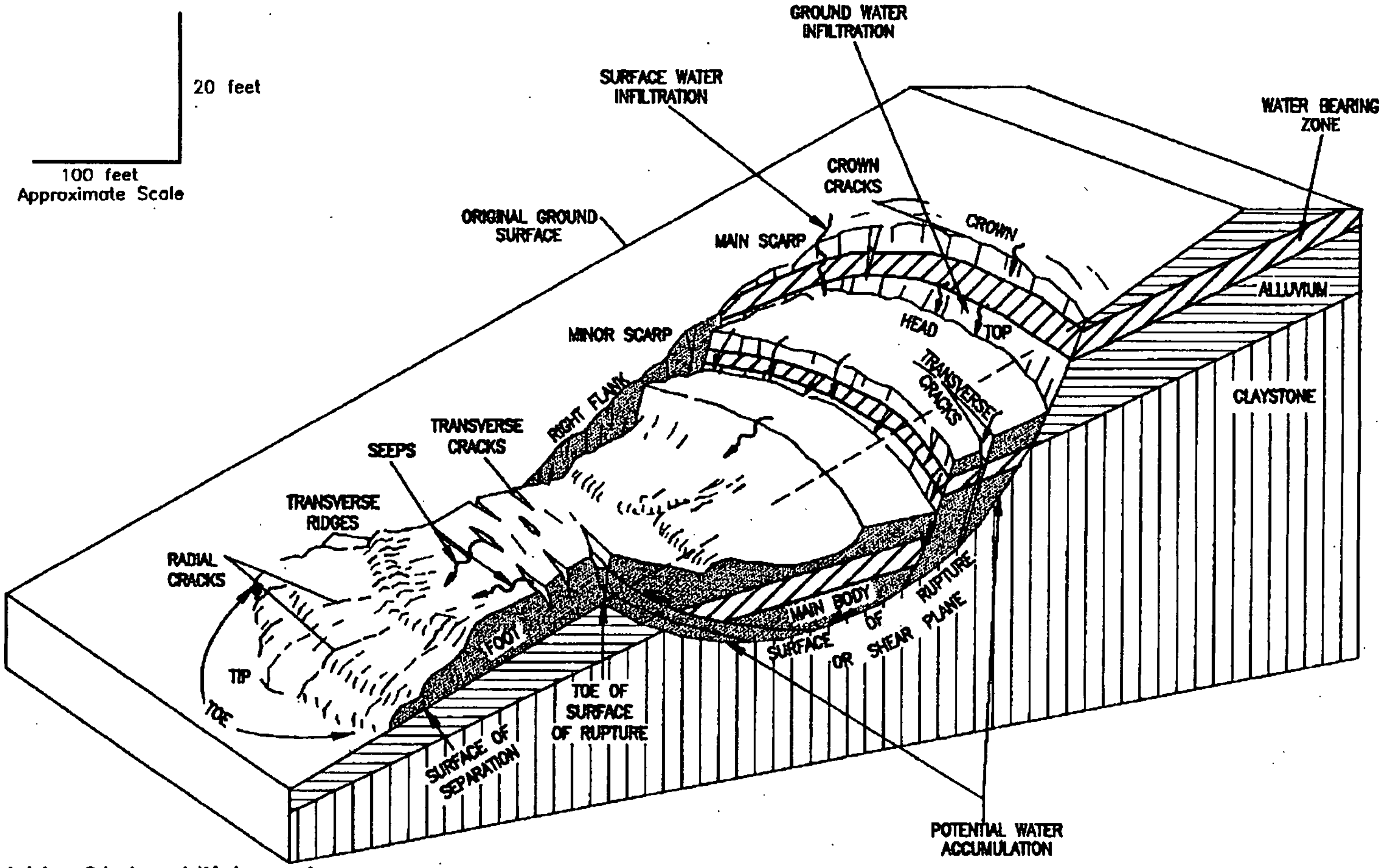

Adapted from Schuster and Krizek, see references.

EG&G ROCKY FLATS

Rocky Flats Site, Golden, Colorado

Potential Hydrogeologic Conditions of a Typical Slump

Hydrogeologic Characterization Report

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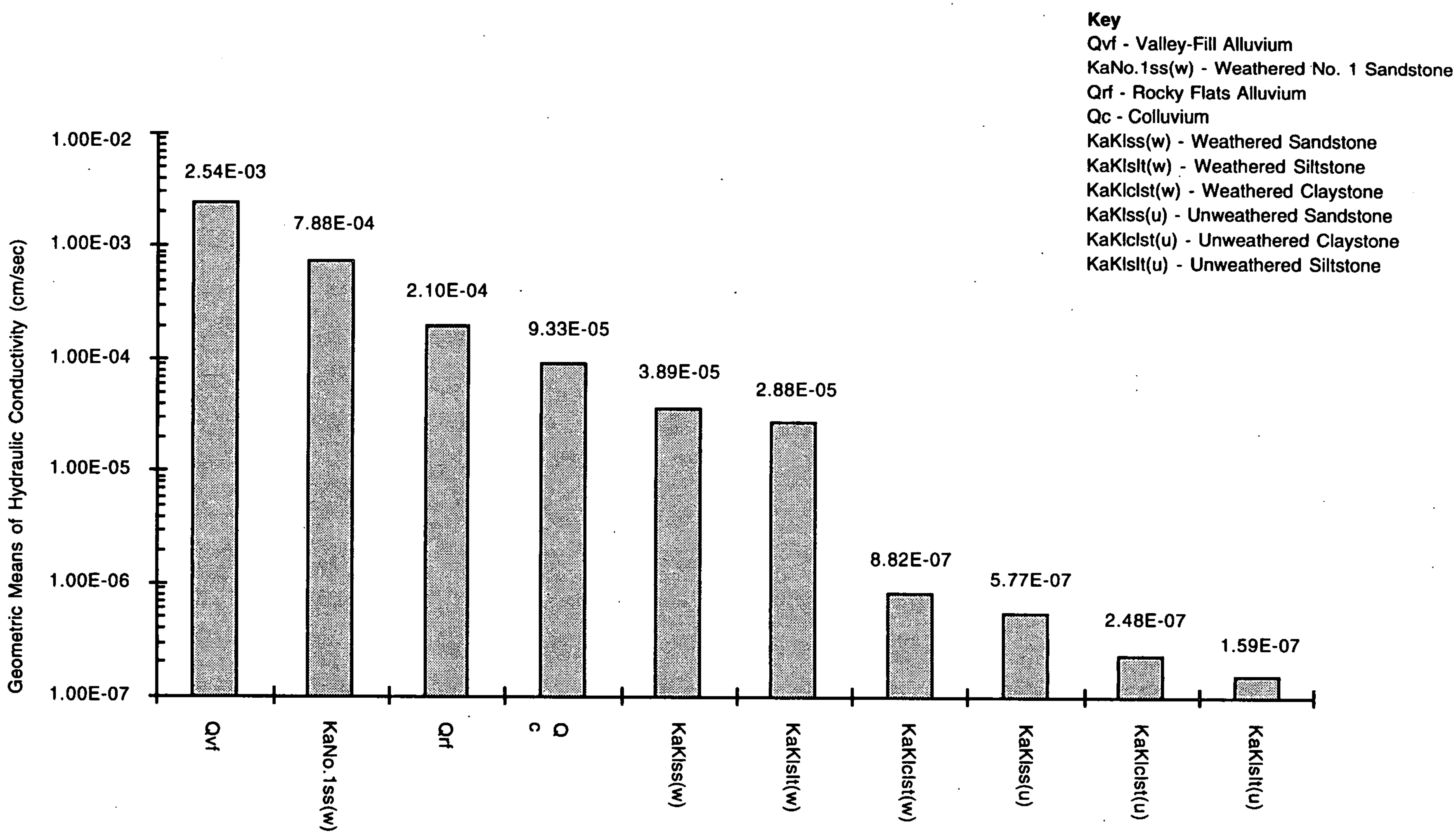

EG&G ROCKY FLATS

Rocky Flats Site, Golden, Colorado

Hydraulic Conductivity of Different Lithologic Units at the Rocky Flats Site

Hydrogeologic Characterization Report

April 1995	Figure 6-18

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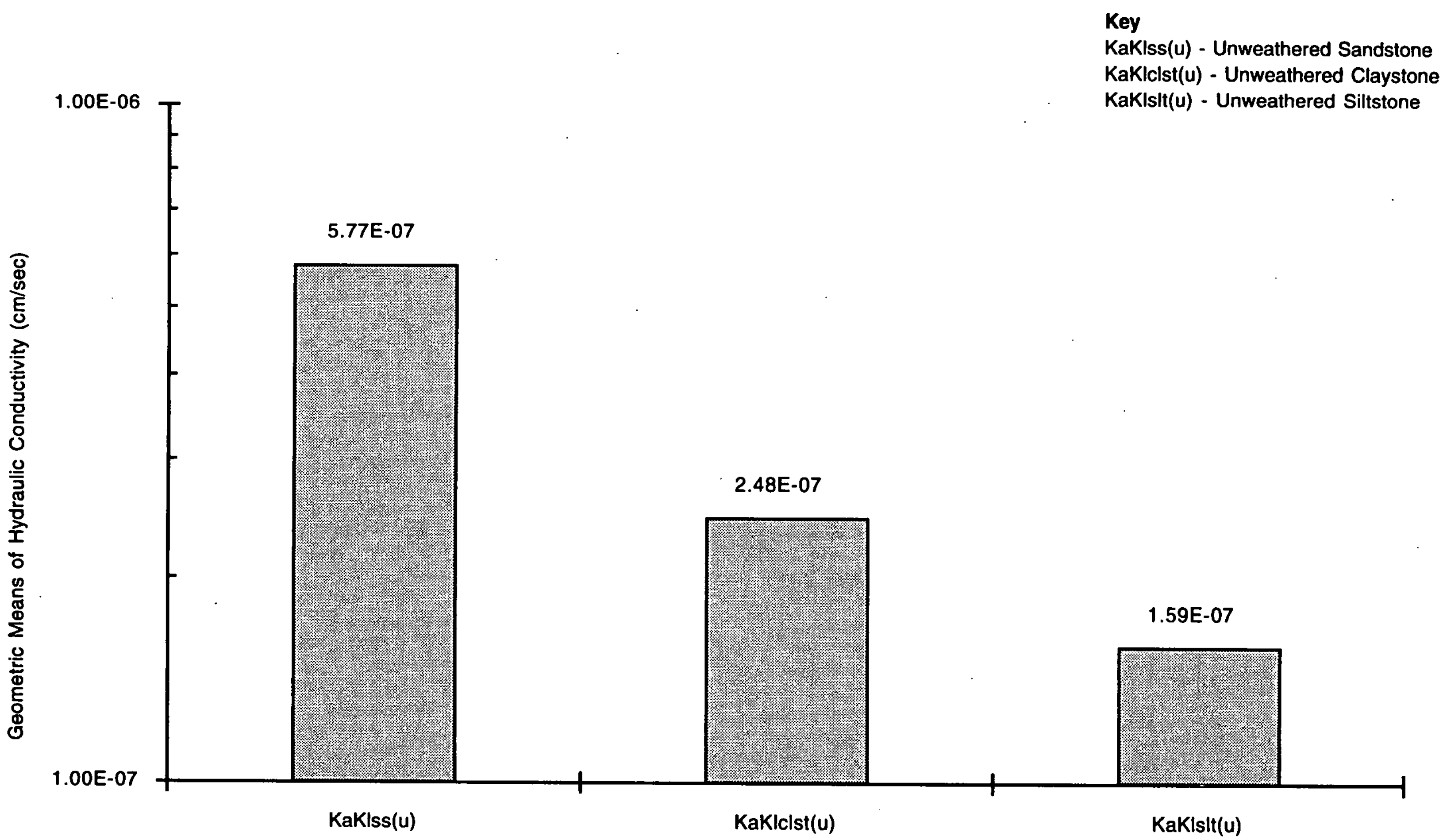

EG&G ROCKY FLATS

Rocky Flats Site, Golden, Colorado

Hydraulic Conductivity of Unweathered Bedrock Units at the Rocky Flats Site

Hydrogeologic Characterization Report

April 1995

Figure 6-20

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7. Recommendations for Additional Groundwater Studies

The following recommendations were compiled to guide future hydrogeologic characterization studies at Rocky Flats. These recommendations address sites that are important for hydrogeologic characterization, potential groundwater pathways for offsite contaminant migration, and characterization of the groundwater flow system at Rocky Flats. This information will be useful for designing groundwater remediation systems at Rocky Flats.

- The influence of the Laramie/Fox Hills subcrop on groundwater flow is unknown. This feature may inhibit groundwater flow in the western portion of the Rocky Flats site and result in lower groundwater levels in the OU11 area. Shallow seismic refraction techniques would be useful for delineating the subcrop and would provide preliminary data useful for designing a drilling program for characterizing the impact of the subcrop on groundwater flow. This characterization will also assist with sitewide groundwater modeling and water-balance efforts.

- The lower drainages, below the terminal ponds in Walnut Creek and Woman Creek, are the primary pathways for offsite migration of contaminated groundwater. However, groundwater flow in these areas is not well characterized. Groundwater wells should be installed to characterize the nature of groundwater flow in the lower drainages below the terminal ponds and to provide sufficient information to determine the groundwater flux across the Indiana Street boundary.

- Nested piezometers should be installed to investigate vertical groundwater flow using screen intervals specifically designed for determining the vertical distribution of head in surficial deposits, weathered bedrock, and unweathered bedrock. These data would be useful for constructing two-dimensional flow net models characterizing the nature of groundwater flow within and between pediments, hillsides, and stream drainages. These data could also be used to characterize vertical groundwater flow within the LHSU.

- The hydrogeologic significance of fault and fracture flow should be investigated. These data would be useful for determining if faults and fractures represent significant pathways for offsite contaminant transport.

- Well logs, geologic logs, and well-construction information should be published as controlled documents so that accurate information is readily available.

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9. Glossary of Terms

alluvial — Pertaining to or composed of alluvium or deposited by a stream or running water.

alluvium — A general term for clay, silt, sand, and gravel, or similar unconsolidated detrital material, deposited during comparatively recent geologic time by a stream or other body of running water, as a sorted or semi-sorted sediment in the bed of the stream or on its flood plain or delta, as a cone or fan at the base of a mountain slope.

anion — A negatively charged ion that migrates to an anode, as in electrolysis.

anisotropy — The condition of having different properties in different directions, as in geologic strata that exhibit different hydraulic conductivities in the vertical and horizontal directions.

aquifer — A water-bearing layer of rock that will yield a significant quantity of water to a well or spring.

bailer-recovery test — Water is removed from a well by bailer, and recovery of water level is measured. Ideally, the time and volume is recorded for each bailer of water removed. However, in typical applications, only the number of bailers removed, total time of bailing, and volume of the bailer are recorded. A bailer-recovery test is differentiated from a slug test by the time of bailing. Although a bailer can be used to remove water during a slug test, all water would need to be removed instantaneously. If the period of bailing is short and the period of water-level recovery is long, for example bailing of five minutes with recovery of two hours, a bailer-recovery test can be interpreted successfully with slug-test methods. However, bailer-recovery tests generally must be interpreted with the This recovery method for constant-rate tests or an appropriate modification to that method.

baseflow — Discharge from groundwater seeping into a surface-water body such as a stream or pond.

bedrock	A general term for the rock, usually solid, that underlies soil or other unconsolidated, superficial material.
caliche	Gravel, sand, or desert debris cemented by porous calcium carbonate.
capillary fringe	The lower subdivision of the zone of aeration, immediately above the water table, in which the interstices are filled with water under pressure less than that of the atmosphere, being continuous with the water below the water table but held above it by surface tension. Its upper body boundary with the intermediate belt is indistinct but is sometimes defined arbitrarily as the level at which 50 percent of the interstices are filled with water.
cataclastic	Pertaining to the structure produced in a rock by the action of severe mechanic stress during dynamic metamorphism or a coarse fragmentation of a rock in transit.
cation	An ion having a positive charge and, in electrolysis, characteristically moving toward a negative electrode.
colluvium	A general term applied to any loose, heterogeneous, and incoherent mass of soil material and/or rock fragments deposited by rainwash, sheetwash, or slow continuous downslope creep, usually collecting at the base of gentle slopes or hillsides.
confined aquifer	A formation in which the groundwater is isolated from the atmosphere at the point of discharge by impermeable geologic formations; confined groundwater is generally subject to pressure greater than atmospheric.
confining layer	A body of material of low hydraulic conductivity that is stratigraphically adjacent to one or more aquifers. It may lie above or below the aquifer.
constant-rate test	Water is removed or introduced to a well at a constant or nearly constant rate for a period generally measured in hours or days. Changes in water level or hydraulic head are measured in the pumping or injection well and nearby observation wells. Water-level changes generally are measured during the pumping or injection period as well as during the subsequent water-level recovery period. The test commonly is called a pumping test if

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water is removed from the well. A wide variety of methods are available to interpret constant-rate tests depending on the hydrogeologic and well characteristics of the test location. A constant head test is an important variation of the constant-rate test and involves placing a hydraulic stress on an aquifer by elevating or depressing the hydraulic head in the well for an extended period.

Darcy's law	A derived equation for the flow of fluids on the assumption that the flow is laminar and that inertia can be neglected. An equation that can be used to compute the quantity of water flowing through an aquifer.
diagenetic	Pertaining to or caused by all the chemical, physical, and biologic changes undergone by a sediment after its initial deposition and during and after its lithification, exclusive of surficial alteration (weathering) and metamorphism.
discharge	The volume of water flowing in a stream or through an aquifer past a specific point in a given period of time.
discharge area	An area in which groundwater is flowing toward the surface and may escape as a spring, seep, or baseflow or by evaporation and transpiration.
downgradient	Direction of decreasing static head.
drainage basin	The land area from which surface runoff drains into a stream channel or system of channels or to a lake, reservoir, or other body of water.
drawdown	*See* slug test.
drawdown recovery test	A lowering of the water table of an unconfined aquifer or the potentiometric surface of a confined aquifer caused by pumping or bailing of groundwater from wells. See bailer-recovery test.
effective porosity	The volume of the void spaces through which water or other fluids can travel in a rock or sediment divided by the total volume of the rock or sediment.

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effluent	A waste liquid discharge from a manufacturing or treatment process, in its natural state or partially or completely treated, that discharges into the environment.
effluent stream	A stream or reach of a stream, the flow of which is being increased by inflow of groundwater.
ephemeral seep	A seep that is intermittent in nature.
equipotential line	A contour line on the water table or potentiometric surface; a line along which the pressure head of groundwater in an aquifer is the same. Fluid flow is normal to these lines in the direction of decreasing fluid potential.
evapotranspiration	Loss of water from a land area through transpiration of plants and evaporation from the soil.
fault	A fracture or a zone of fractures along which there has been displacement of the sides relative to one another parallel to the fracture.
flow lines	Lines indicating the direction of groundwater flow toward points of discharge. Flow lines are perpendicular to equipotential lines.
frequency distribution	The numerical or quantitative distribution of objects or material in a series of closely related classes. It is generally selected on the basis of some progressively variable physical characteristic.
gaining stream	A stream or reach of a stream, the flow of which is being increased by inflow of ground water. Also known as an effluent stream.
heterogeneous	Nonuniform in structure or composition throughout.
hydraulic conductivity	A coefficient of proportionality describing the rate at which water can move through a permeable medium. The density and kinematic viscosity of the water must be considered in determining hydraulic conductivity.
hydraulic connection	Two units are in complete hydraulic connection when a change in head in one unit is immediately reflected in the other.

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hydraulic gradient	The rate of change in total head per unit of distance of flow in a given direction.
hydraulic head	The sum total of elevation and pressure head.
hydrograph	A graph that shows some property of ground water or surface water as a function of time.
hydrostratigraphic unit	A formation, part of a formation, or group of formations in which there are similar hydrologic characteristics allowing for grouping into aquifers or confining layers.
infiltration	The flow of water downward from the land surface into and through the upper soil layers.
influent stream	A stream or reach of a stream that is losing water by seepage into the ground.
interflow	The lateral movement of water in the unsaturated zone during and immediately after a precipitation event. The water moving as interflow discharges directly into a stream or lake.
intermittent seep	A seep that discharges only periodically.
isopach	A line drawn on a map through points of equal true thickness of a designated stratigraphic unit, group of stratigraphic units, or hydrostratigraphic unit.
isotropic	The condition in which hydraulic properties of the aquifer are equal in all directions.
kurtosis	The peakedness or flatness of the graphic representation of a statistical distribution; specifically, a measure of the peakedness of a frequency distribution.
leptokurtic	Said of a frequency distribution that has a concentration of values about its mean greater than for the corresponding normal distribution; a very peaked distribution.
lithostratigraphic unit	A rock unit that is distinctive in its physical characteristics, including hand specimen and outcrop descriptions, based on such characteristics as color, mineralogic composition, and grain size.

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losing stream	A stream or reach of a stream that is losing water by seepage into the ground. Also known as an influent stream.
lower hydro-stratigraphic unit	At the Rocky Flats site, the lower hydrostratigraphic unit consists of unweathered bedrock. Also known as LHSU.
macropore flow	A type of preferential flow that occurs in large pores or cracks at or near saturation that can result in the rapid bypass of water and dissolved chemicals through the soil.
mesokurtic	Closely resembling a normal frequency distribution; e.g., said of a distribution curve that is neither leptokurtic (very peaked) nor platykurtic (flat across the top).
meteoric water	Pertaining to water of recent atmospheric origin.
packer test	A packer test generally is conducted in an open hole and may be conducted in either saturated or unsaturated conditions. Packers are used to isolate a portion of the hole, and a series of constant pressure tests are conducted. The rate of water injection is measured. Ideally, the injection rate is monitored until it stabilizes, indicating steady-state conditions have occurred. However, the typical test procedure involves injecting for a specified time, generally measured in minutes, and recording either the final injection rate or the average injection rate. Test results generally are interpreted by a modification of the Theim equation.
paleochannel	A remnant of a stream channel cut in older rock and filled by the sediments of younger overlying rock.
pediment	A broad, gently sloping rock-floored erosion surface or plain of low relief, typically developed by subaerial agents in an arid or semiarid region at the base of an abrupt and receding mountain front or plateau escarpment and underlain by bedrock.
perched water table	Unconfined ground water separated from an underlying main body of ground water by an unsaturated zone.
perennial seep	A seep that flows continuously, as opposed to an intermittent seep or a periodic seep.

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permeability	The property or capacity of a porous rock, sediment, or soil for transmitting a fluid; it is a measure of the relative ease of fluid flow under unequal pressure.
permeameter test	A laboratory test using a permeameter to measure the intrinsic permeability and hydraulic conductivity of a soil or rock sample.
phreatophyte	A type of plant that typically has a high rate of transpiration by virtue of a taproot extending to the water table.
piezometer	A nonpumping well, generally of small diameter, that is used to measure the elevation of the water table or potentiometric surface. A piezometer generally has a short well screen through which water can enter.
platykurtic	Said of a frequency distribution that has a concentration of values about its mean less than for the corresponding normal distribution; a distribution that is flat across the top.
porosity	The percentage of the bulk volume of a rock or soil that is occupied by interstices, whether isolated or connected.
potentiometric surface	An imaginary surface representing the total head of groundwater in a confined or unconfined aquifer that is defined by the level to which water will rise in a well.
preferential flow	Refers to any mechanism that results in flow in isolated regions or channels that bypass the soil matrix.
recharge	The addition of water to the zone of saturation; also, the amount of water added.
runoff	That part of precipitation flowing to surface streams.
saturated zone	The zone in which the voids in the rock or soil are filled with water at a pressure greater than atmospheric. The water table is the top of the saturated zone in an unconfined aquifer.
secondary permeability	The permeability that has been caused by fractures or weathering in a rock or sediment after it has been formed.

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semi-confined	A confined aquifer that can lose or gain water through either or both of the formations bounding it. Although flow may be limited through the bounding formations, over large areas significant quantities of water may flow into or out of the aquifer.
skewness	The condition of being disordered or lacking symmetry; specifically, the state of asymmetry shown by a frequency distribution that is bunched on one side of the average and tails off on the other side.
slug test	A known volume or "slug" of water is suddenly injected into or removed from a well and the decline or recovery of water level is measured. If conducted by instantaneously adding water, the test may be referred to as a "slug in" test. If conducted by instantaneously removing water, the test may be referred to as a "slug out" test. As an alternative to instantaneous injection or removal of water, a weight of known volume may be suddenly introduced or removed from the well. Slug tests originally were developed to evaluate low-permeability hydrogeologic units. However, with improvements in pressure transducer and data-logger technology, slug tests have found wide application in contaminated aquifers where the large hydraulic stresses of long-term tests are not advisable. The duration of a test generally is measured in minutes. However, test duration exceeding an hour is common in low-permeability rock. Methods of test analysis have been developed for fully penetrating and partially penetrating wells under confined or water-table conditions. Methods for analysis of both porous media and fractured media are available.
specific yield	The ration of the volume of water that a given mass of saturated rock or soil will yield by gravity to the volume of that mass. This ratio is stated as a percentage.
static water level	The level of water in a well that is not being affected by withdrawal of groundwater.
storativity	The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. It is equal to the product of specific storage and aquifer thickness. In an unconfined aquifer, the storativity is equivalent to the specific yield. Also called storage coefficient.

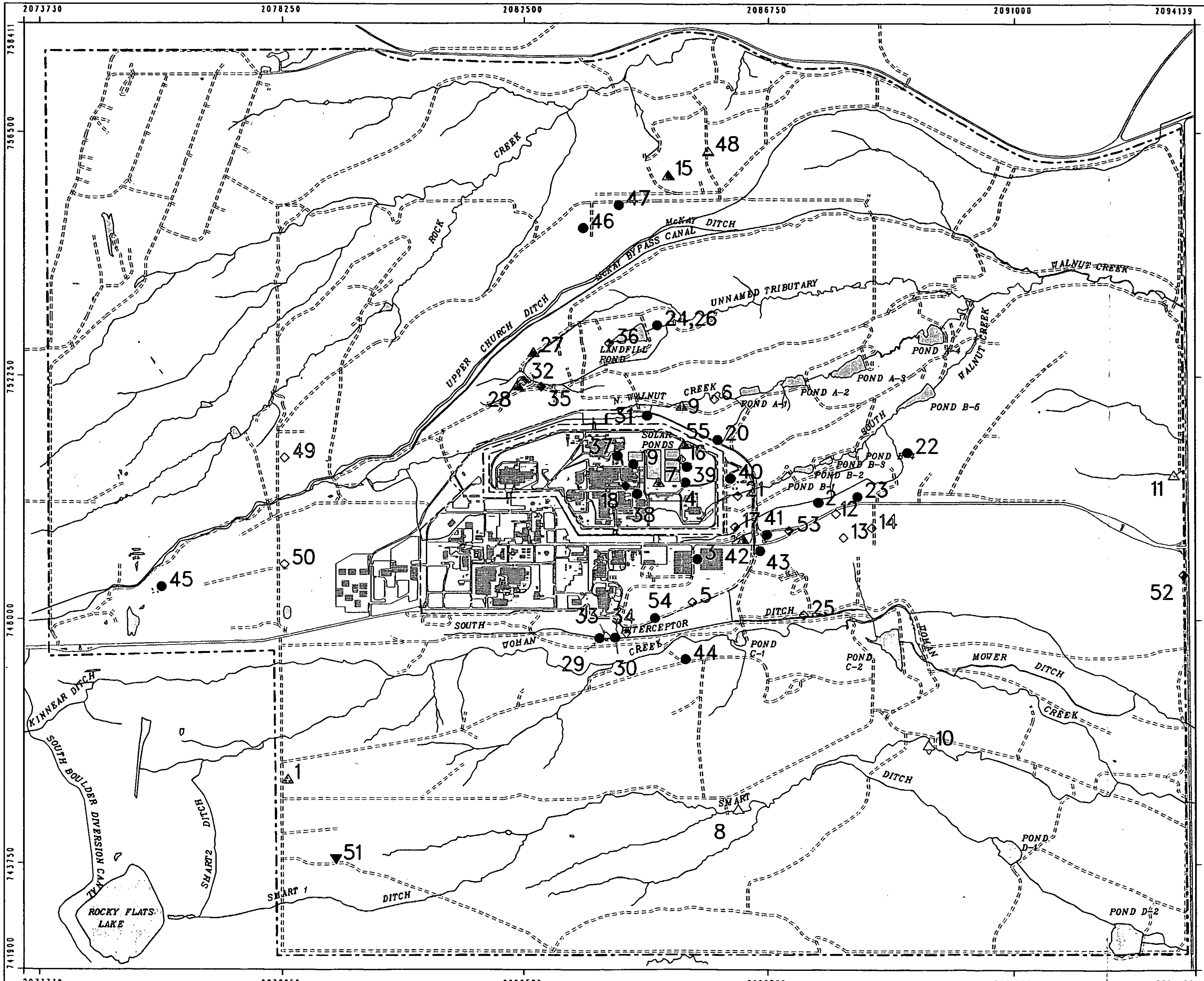
225

stratigraphic unit	A stratum or body of adjacent strata recognized as a unit in the classification of a rock sequence with respect to any of the many characters, properties, or attributes that rocks may possess, for any purpose such as description, mapping, and correlation.
subcrop	An occurrence of strata in contact with the undersurface of an inclusive stratigraphic unit that succeeds an important unconformity of which overstep is conspicuous; a "subsurface outcrop" that describes the areal limits of a truncated rock unit at a buried surface of unconformity.
topography	The natural or physical surface features of a region, considered collectively as to form the features revealed by the contour lines of a map.
transmissivity	The rate at which water of a prevailing density and viscosity is transmitted through a unit width of an aquifer or confining bed under a unit hydraulic gradient. It is a function of properties of the liquid, the porous media, and the thickness of the porous media.
transpiration	The process by which plants give off water vapor through their leaves.
unconfined aquifer	An aquifer where the water table is exposed to the atmosphere through openings in the overlying materials.
unsaturated zone	The zone between the land surface and the water table. It includes the root zone, intermediate zone, and capillary fringe. The pore spaces contain water at less than atmospheric pressure, as well as air and other gases. Saturated bodies, such as perched ground water, may exist in the unsaturated zone. Also called zone of aeration and vadose zone.
upgradient	Direction of increasing static head.
upper hydro-stratigraphic unit	At the Rocky Flats site, the upper hydrostratigraphic unit consists of all unconsolidated surficial materials and weathered bedrock. Also known as UHSU.
vadose zone	*See* unsaturated zone.
valley fill	The unconsolidated sediment deposited by an agent so as to fill or partly fill a valley.

226

water table	The surface between the vadose zone and the groundwater; that surface of a body of unconfined ground water at which the pressure is equal to that of the atmosphere.
watershed	*See* drainage basin.
δD	The deuterium isotopic composition of water expressed as parts-per-thousand difference from standard mean ocean water.
$\delta^{18}O$	The ^{18}O isotopic composition of water expressed as parts-per-thousand difference from standard mean ocean water.

227 | 227



EXPLANATION

Completion Zone

- ● Alluvium, Weathered Bedrock
- ◇ Alluvium, Unweathered Bedrock
- △ Alluvium, Weathered Bedrock, Unweathered Bedrock
- ▼ Alluvium Only

- Streams and Drainages
- Paved Roads
- Dirt Roads
- Rocky Flats Plant Site and Security Zone Boundaries
- Rocky Flats Site Boundary
- Surface Water Impoundments
- Buildings

Scale = 1 : 20400
1 inch = 1700 feet

850 0 1700ft

State Plane Coordinate System
Colorado Central Zone
Datum: NAD27

EG&G ROCKY FLATS

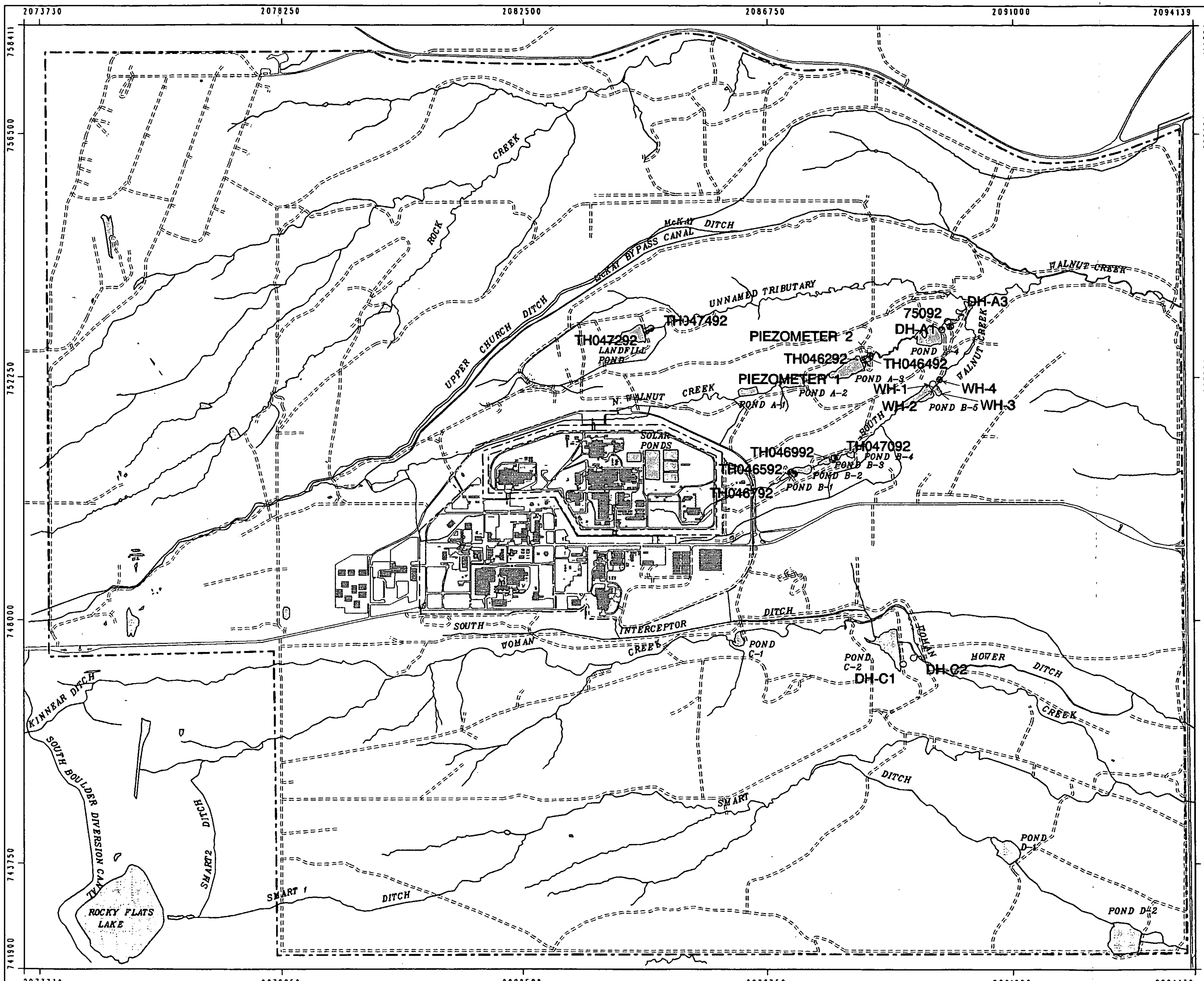
Rocky Flats Site, Golden, Colorado

Locations of Well Clusters

Hydrogeologic Characterization Report

April 1995	Figure D-1

660



EXPLANATION

- Piezometer
- Monitoring Well

NOTE: Piezometer 1 and Piezometer 2 are approximately located.

- Streams and Drainages
- Paved Roads
- Dirt Roads
- Rocky Flats Plant Site and Security Zone Boundaries
- Rocky Flats Site Boundary
- Surface Water Impoundments
- Buildings

N

Scale = 1 : 20400
1 inch = 1700 feet

850 0 1700ft

State Plane Coordinate System
Colorado Central Zone
Datum: NAD27

EG&G ROCKY FLATS

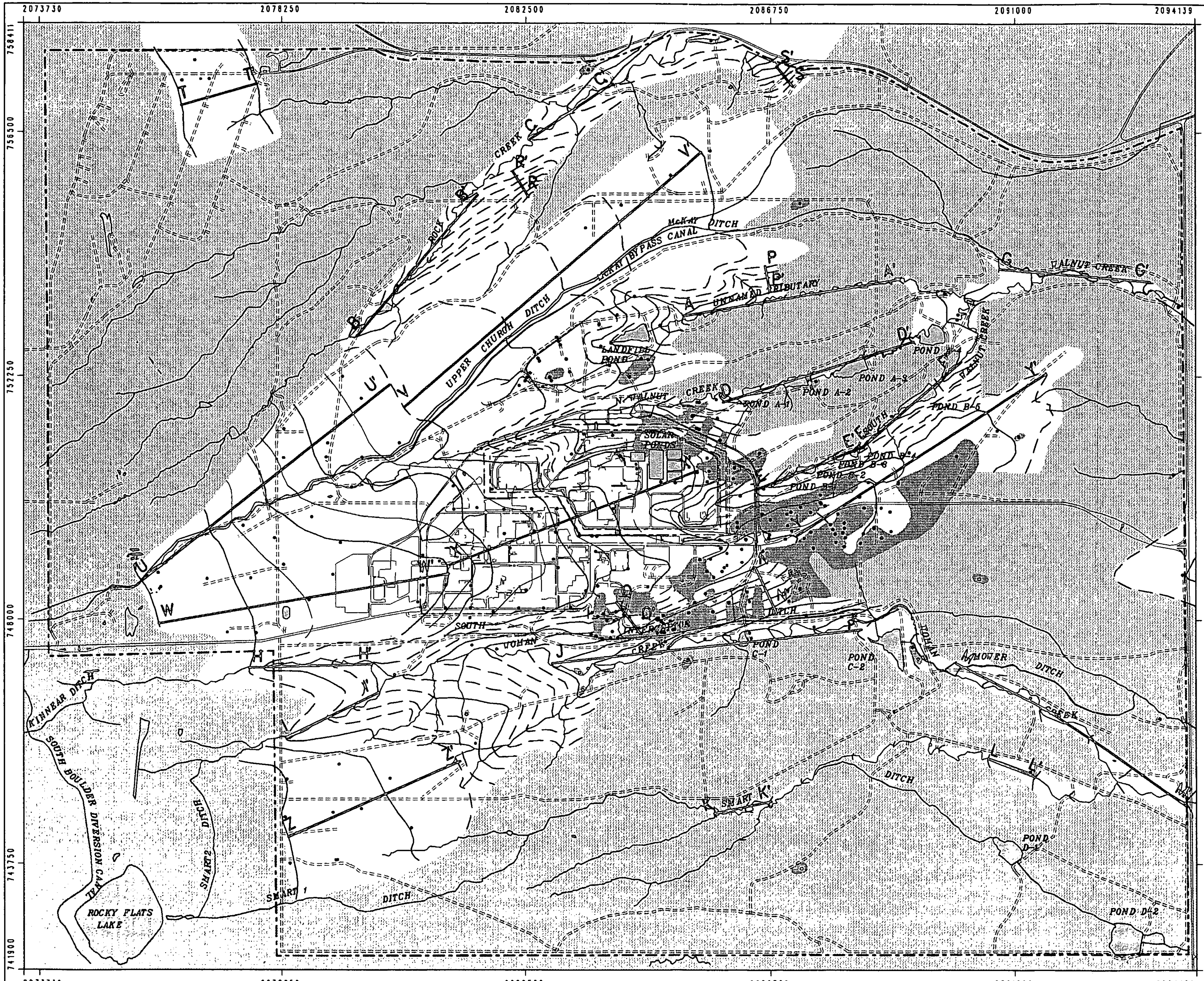
Rocky Flats Site, Golden, Colorado

Dam Piezometer Location Map

Hydrogeologic Characterization Report

April 1995	Figure E-1

717



EXPLANATION

- Flow Path
- Water Level Contour
- Intermediate Water Level Contour
- Approximate Extent of Unsaturated Areas
- Areas Without Groundwater Elevation Data
- Streams and Drainages
- Paved Roads
- Dirt Roads
- Rocky Flats Plant Site and Security Zone Boundaries
- Rocky Flats Site Boundary
- Surface Water Impoundments

N

Scale = 1 : 20400
1 inch = 1700 feet

850 0 1700ft

State Plane Coordinate System
Colorado Central Zone
Datum: NAD27

EG&G ROCKY FLATS

Rocky Flats Site, Golden, Colorado

Approximate Location of Flow Paths Used to Calculate Hydraulic Gradients for Qrf, Qc, and Qvf

Hydrogeologic Characterization Report

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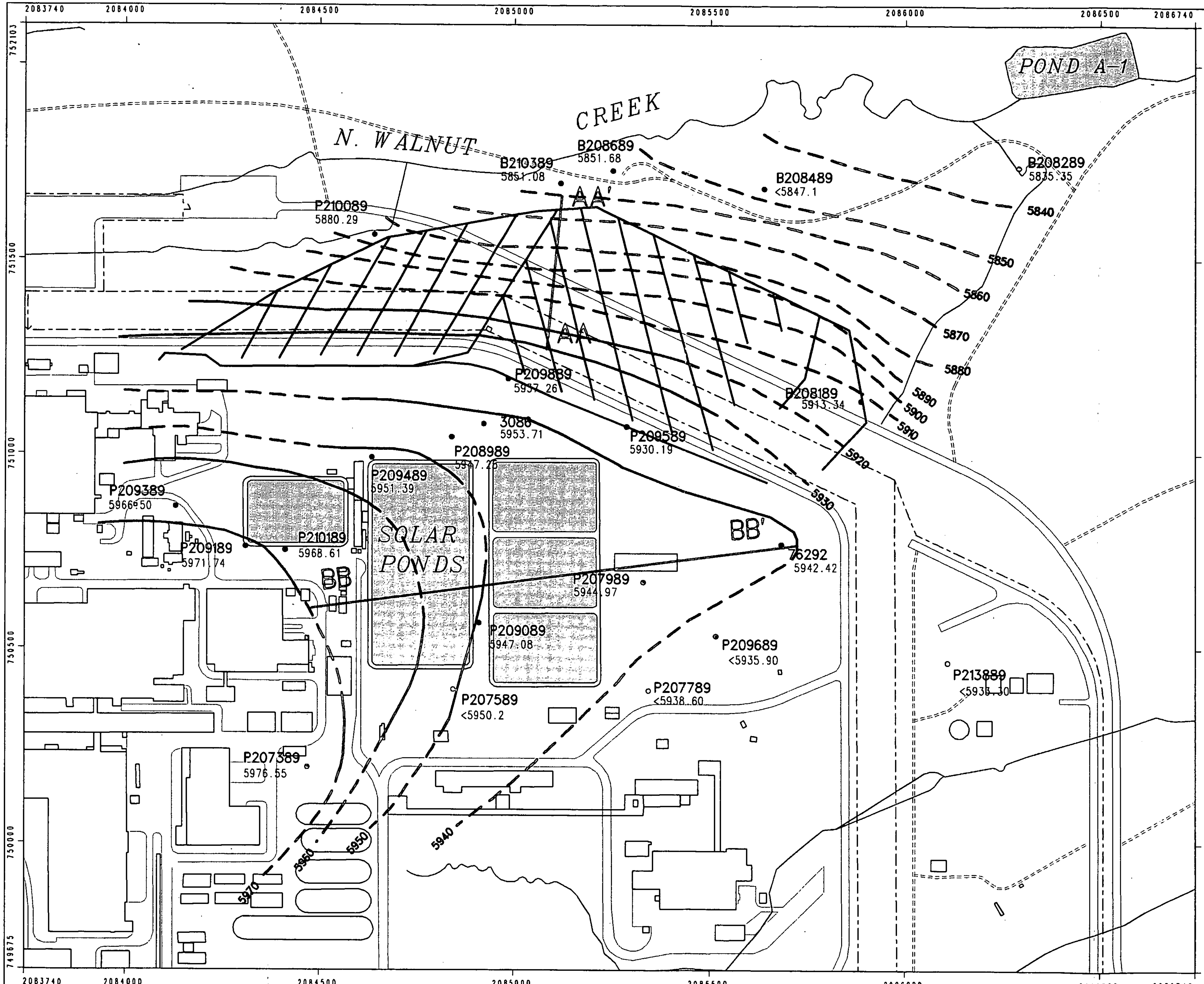
810



EXPLANATION

- Weathered Bedrock Well
- Line of Equal Potentiometric Surface
- (dashed where inferred)
- Flow Path
- Streams and Drainages
- Paved Roads
- Dirt Roads
- Rocky Flats Plant Site and Security Zone Boundaries
- French Drain
- Surface Water Impoundments
- Buildings

N

Scale = 1 : 3000
1 inch = 250 feet

125 0 250ft

State Plane Coordinate System
Colorado Central Zone
Datum: NAD27

EG&G ROCKY FLATS

Rocky Flats Site, Golden, Colorado

Potentiometric Surface and Flow Path of Weathered Bedrock at Solar Ponds Area
April 1993
(from: EG&G, 1994b)

Hydrogeologic Characterization Report

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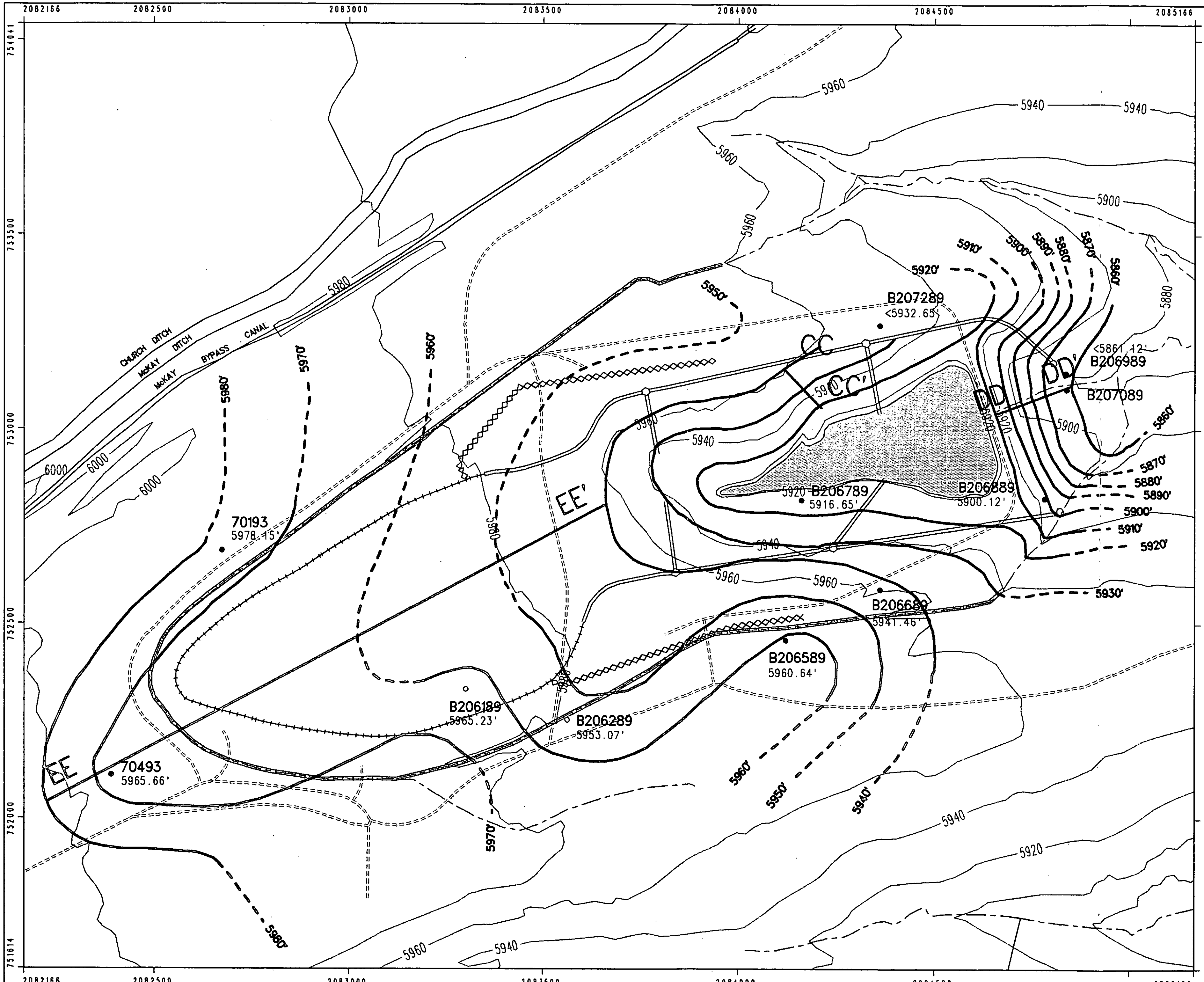
811



EXPLANATION

- Bedrock Well
- Line of Equal Potentiometric Surface
- (dashed where inferred)
- Flow Path
- Dirt Roads
- Topographic Contours
- Streams and Ditches
- Intermittent Streams
- Surface-Water Diversion Ditch
- Slurry Wall
- Groundwater Intercept System
- (perforated)
- (non-perforated)

Scale = 1 : 3000
1 inch = 250 feet

State Plane Coordinate System
Colorado Central Zone
Datum: NAD27

EG&G ROCKY FLATS

Rocky Flats Site, Golden, Colorado

Potentiometric Surface and Flow Path of Weathered Bedrock at Present Landfill Area March 1993 (from: DOE, 1994a)

Hydrogeologic Characterization Report

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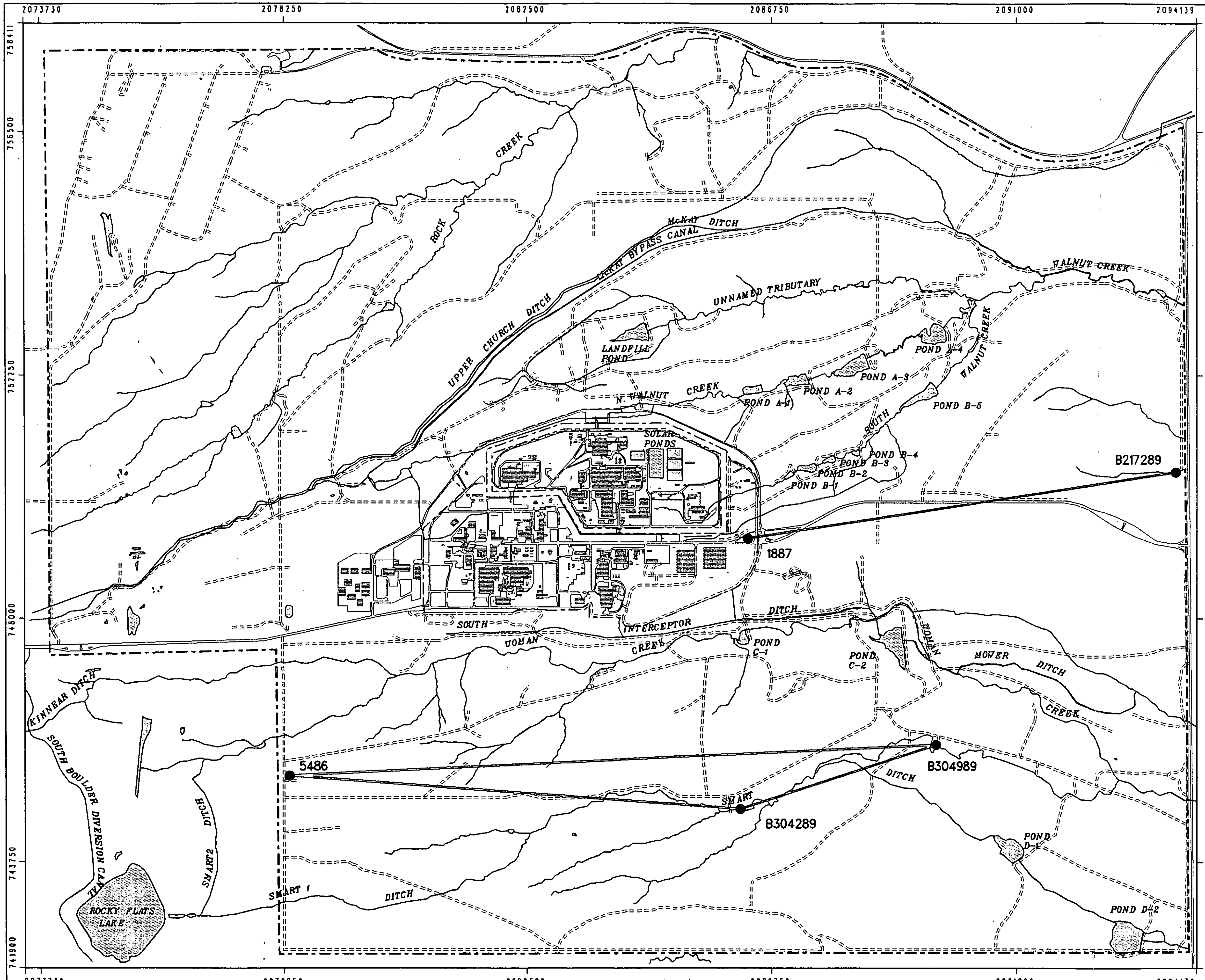
812



EXPLANATION

- Unweathered Bedrock Well
- Flow Path
- Streams and Drainages
- Paved Roads
- Dirt Roads
- Rocky Flats Plant Site and Security Zone Boundaries
- Rocky Flats Site Boundary
- Surface Water Impoundments
- Buildings

N

Scale = 1 : 20400
1 inch = 1700 feet

850 0 1700ft

State Plane Coordinate System
Colorado Central Zone
Datum: NAD27

EG&G ROCKY FLATS

Rocky Flats Site, Golden, Colorado

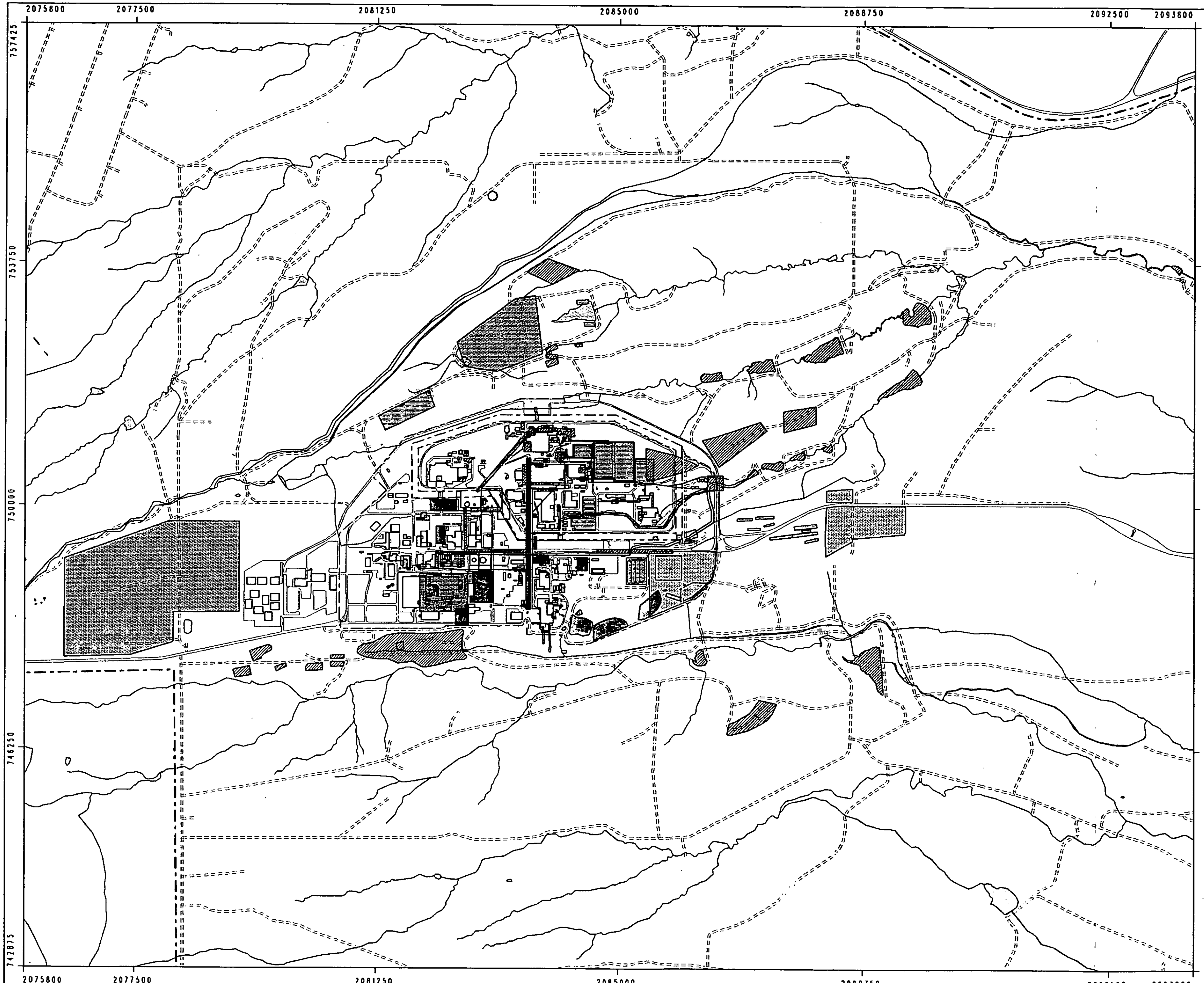
LHSU Flow Paths Used to Calculate Hydraulic Gradients

Hydrogeologic Characterization Report

April 1995

Figure G-8

813



EG&G ROCKY FLATS

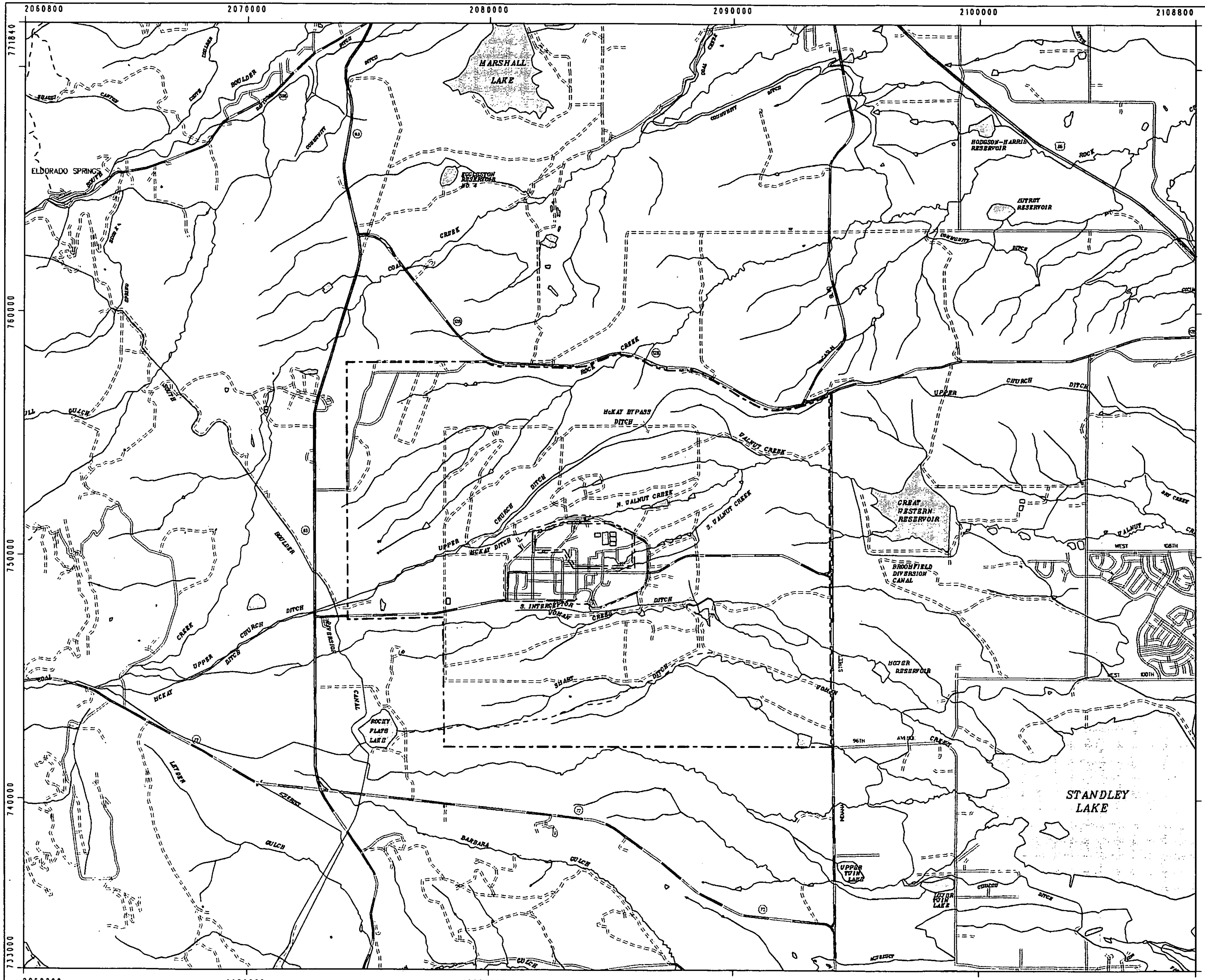
Rocky Flats Site, Golden, Colorado

Individual Hazardous Substance Sites and Operable Units at the Rocky Flats Site

Hydrogeologic Characterization Report

April 1995

Figure 1-2



EG&G ROCKY FLATS

Rocky Flats Site, Golden, Colorado

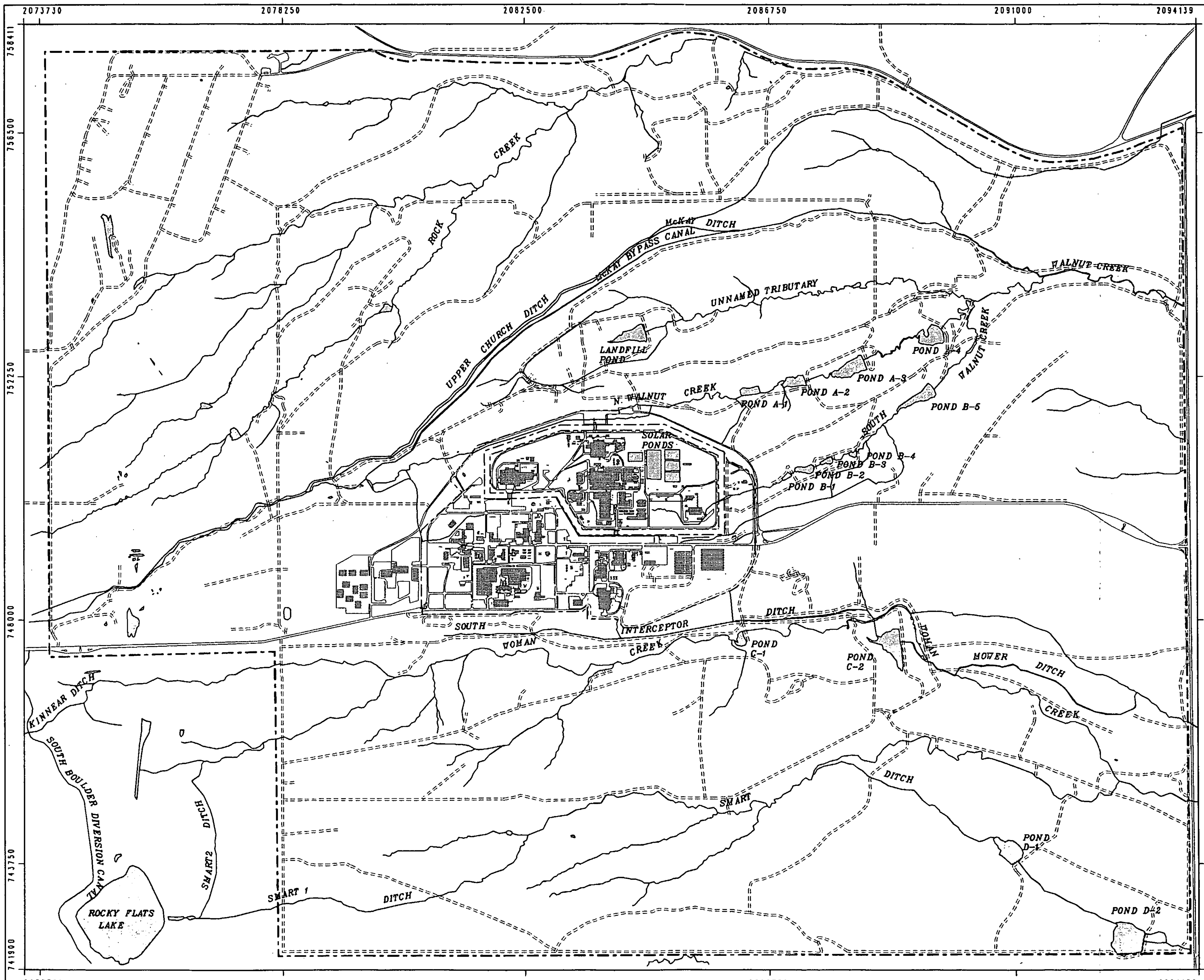
Surface Water Features of Rocky Flats Site and Vicinity

Hydrogeologic Characterization Report

April 1995

Figure 3-4

51



EXPLANATION

- Surface Water Impoundments
- Streams and Drainages
- Paved Roads
- Dirt Roads
- Rocky Flats Plant Site and Security Zone Boundaries
- Rocky Flats Site Boundary
- Buildings

N

Scale = 1 : 20400
1 inch = 1700 feet

850 0 1700ft

State Plane Coordinate System
Colorado Central Zone
Datum: NAD27

EG&G ROCKY FLATS

Rocky Flats Site, Golden, Colorado

Surface Water Features
of
Rocky Flats Site

Hydrogeologic Characterization Report

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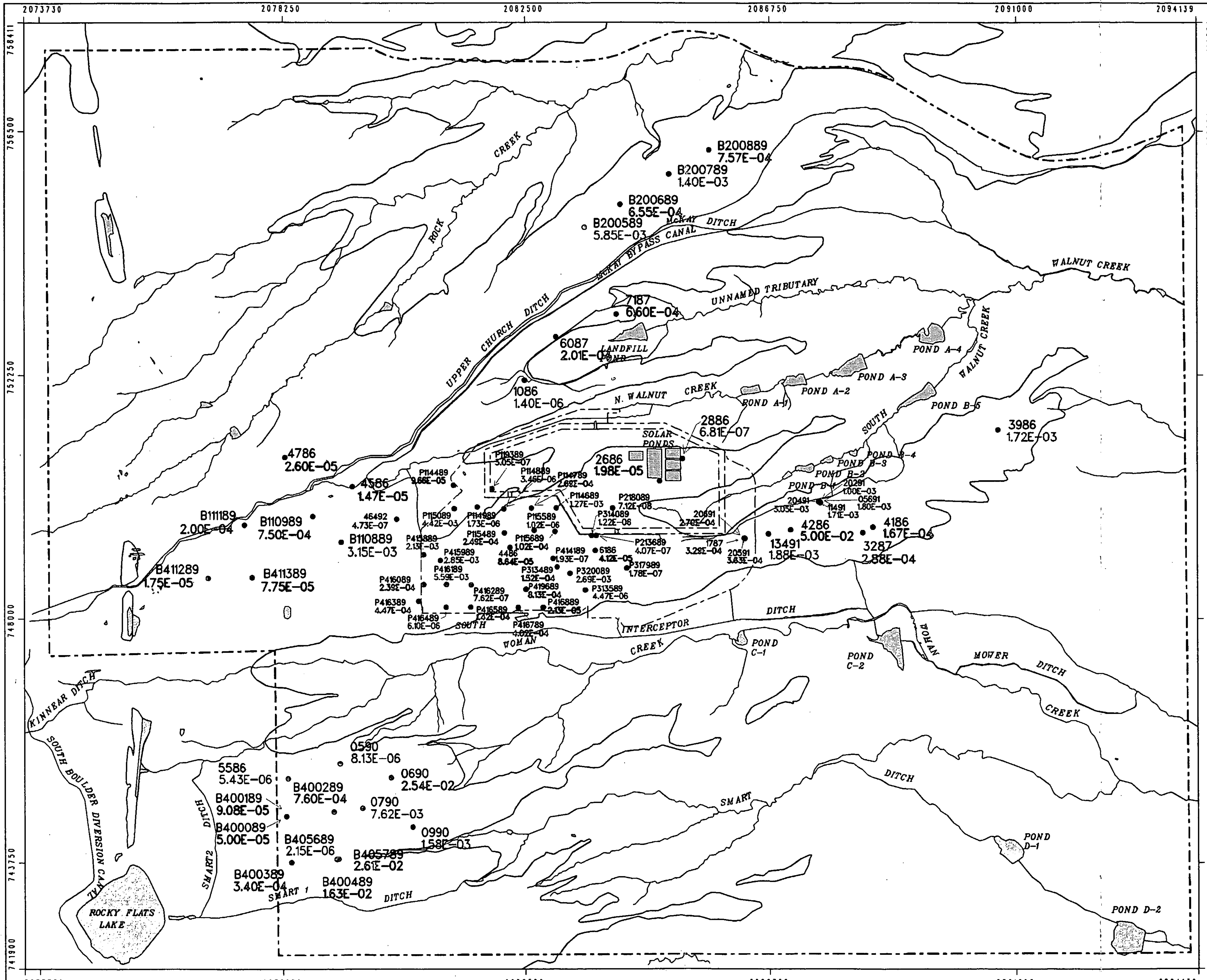
52



EXPLANATION

- Wells with Hydraulic Conductivity Data

Values Reported in Centimeters/Second

Color Chart for Hydraulic Conductivity Ranges

- E -02
- E -03
- E -04
- E -05
- E -06
- E -07
- Streams and Drainages
- Approximate Extent of Rocky Flats Alluvium
- Rocky Flats Plant Site and Security Zone Boundaries
- Rocky Flats Site Boundary
- Surface Water Impoundments

N

Scale = 1 : 20400
1 inch = 1700 feet

850 0 1700ft

State Plane Coordinate System
Colorado Central Zone
Datum: NAD27

EG&G ROCKY FLATS

Rocky Flats Site, Golden, Colorado

Hydraulic Conductivity of Rocky Flats Alluvium (Qrf)

Hydrogeologic Characterization Report

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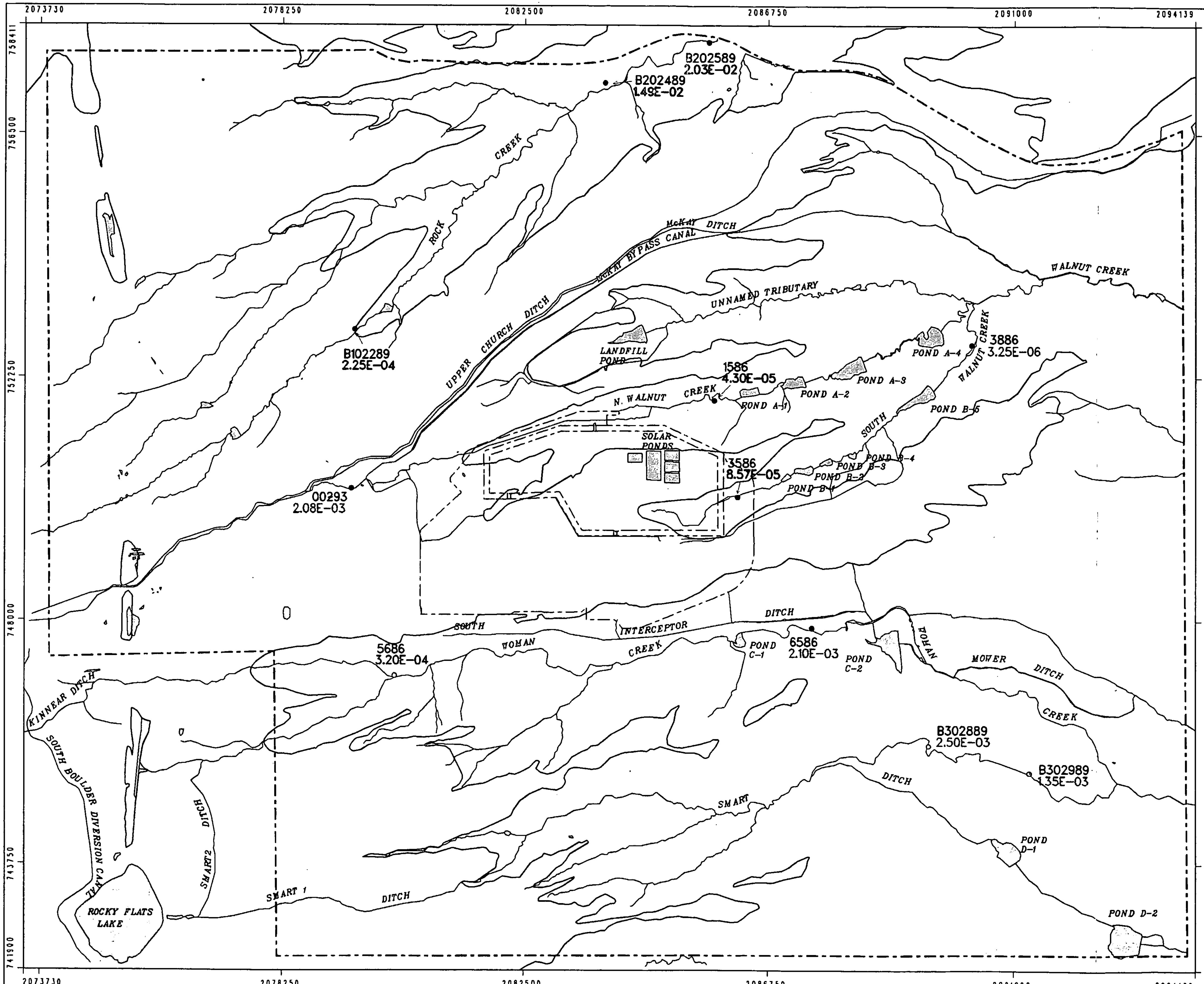
188



EXPLANATION

- Wells with Hydraulic Conductivity Data

Values Reported In Centimeters/Second

Color Chart for Hydraulic Conductivity Ranges

- E -02
- E -03
- E -04
- E -05
- E -06
- Streams and Drainages
- Approximate Extent of Rocky Flats Alluvium
- Rocky Flats Plant Site and Security Zone Boundaries
- Rocky Flats Site Boundary
- Surface Water Impoundments

N

Scale = 1 : 20400
1 inch = 1700 feet

850 0 1700ft

State Plane Coordinate System
Colorado Central Zone
Datum: NAD27

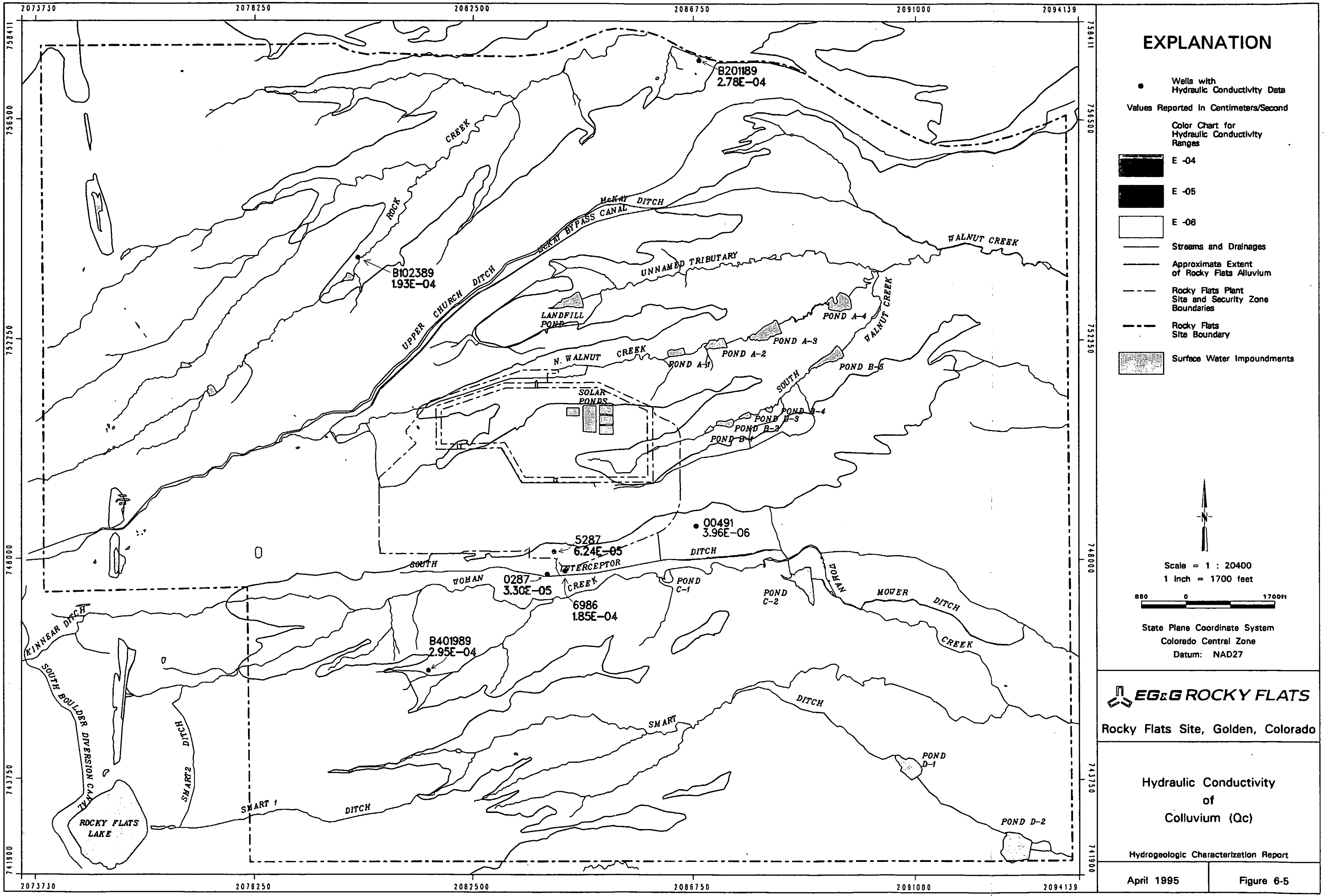
EG&G ROCKY FLATS

Rocky Flats Site, Golden, Colorado

Hydraulic Conductivity
of
Valley Fill Alluvium (Qvf)

Hydrogeologic Characterization Report

April 1995 | Figure 6-4



EXPLANATION
Wells with Hydraulic Conductivity Data
Values Reported in Centimeters/Second
Color Chart for Hydraulic Conductivity Ranges
E -04
E -05
E -06
Streams and Drainages
Approximate Extent of Rocky Flats Alluvium
Rocky Flats Plant Site and Security Zone Boundaries
Rocky Flats Site Boundary
Surface Water Impoundments
Scale = 1 : 20400
1 inch = 1700 feet
State Plane Coordinate System
Colorado Central Zone
Datum: NAD27
EG&G ROCKY FLATS
Rocky Flats Site, Golden, Colorado
Hydraulic Conductivity of Colluvium (Qc)
Hydrogeologic Characterization Report
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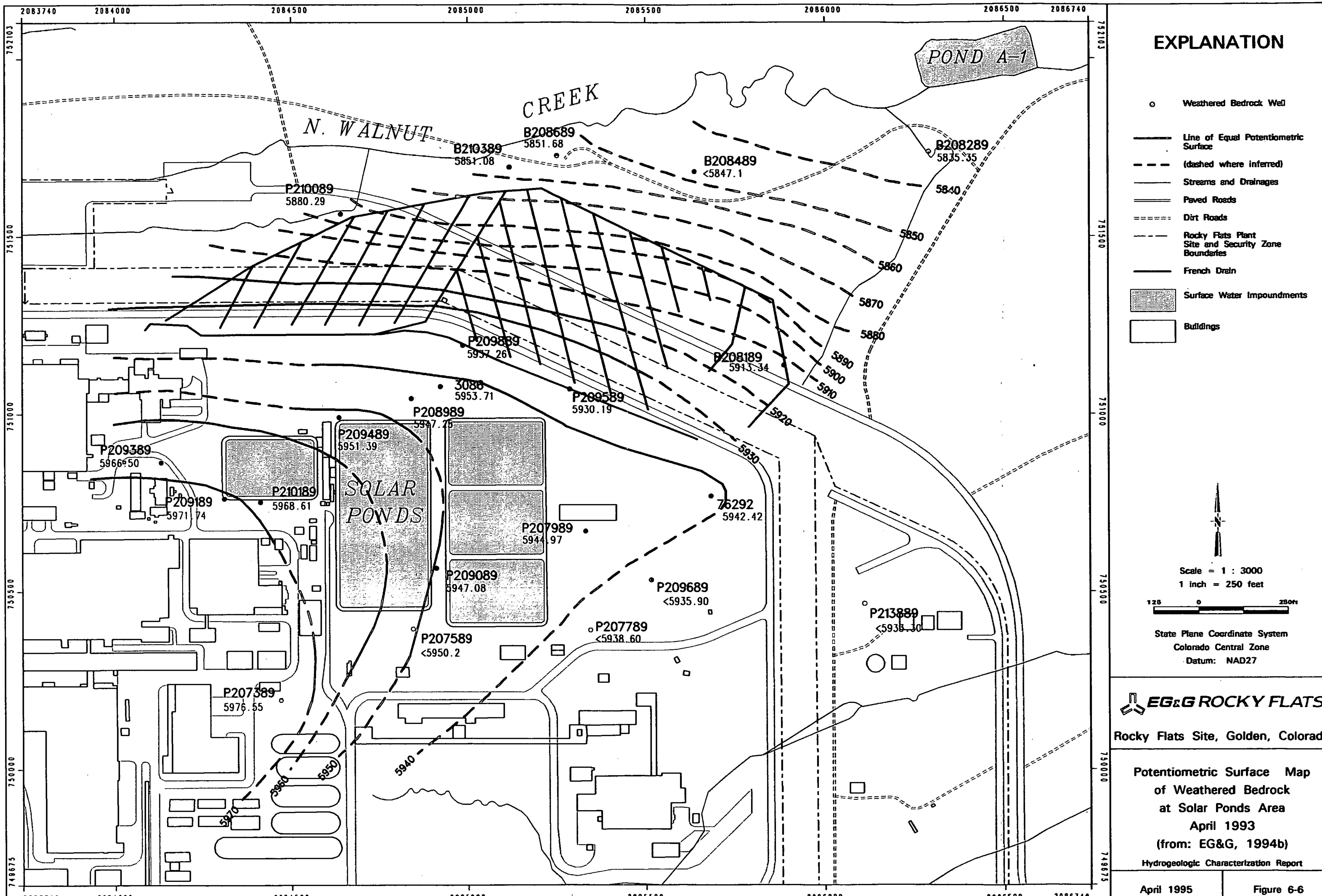
Figure 6-5
2073730
2078250
2082500
2086750
2091000
2094139
758411
756500
752250
748000
743750
741900
B201189
2.78E-04
B102389
1.93E-04
00491
3.96E-06
5287
6.24E-05
0287
3.30E-05
6986
1.85E-04
B401989
2.95E-04
ROCK CREEK
McKAY DITCH
McKAY BYPASS CANAL
UPPER CHURCH DITCH
UNNAMED TRIBUTARY
WALNUT CREEK
LANDFILL POND
N. WALNUT CREEK
POND A-1
POND A-2
POND A-3
POND A-4
POND B-1
POND B-2
POND B-3
POND B-4
POND B-5
SOUTH WALNUT CREEK
SOLAR PONDS
SOUTH INTERCEPTOR DITCH
WOMAN CREEK
POND C-1
POND C-2
MOWER DITCH
KINNEAR DITCH
SOUTH BOULDER DIVERSION CANAL
SMART 2 DITCH
SMART 1 DITCH
SMART DITCH
ROCKY FLATS LAKE
POND D-1
POND D-2



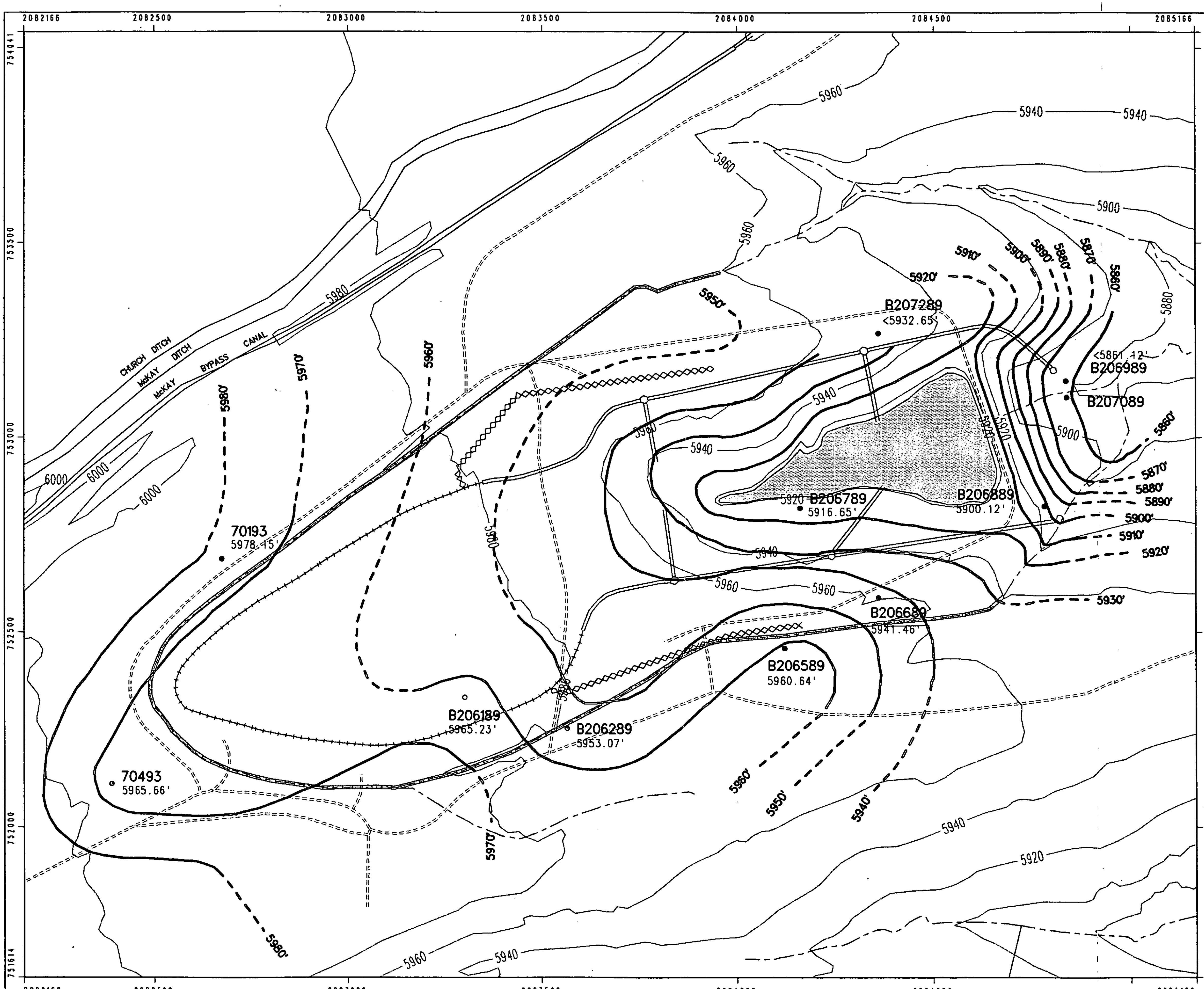
EG&G ROCKY FLATS

Rocky Flats Site, Golden, Colorado

Potentiometric Surface Map of Weathered Bedrock at Solar Ponds Area April 1993 (from: EG&G, 1994b)

Hydrogeologic Characterization Report

April 1995 | Figure 6-6



EXPLANATION

- Bedrock Well
- Line of Equal Potentiometric Surface
- (dashed where inferred)
- Dirt Roads
- Topographic Contours
- Streams and Ditches
- Intermittent Streams
- Surface-Water Diversion Ditch
- Slurry Wall
- Groundwater Intercept System
- (perforated)
- (non-perforated)

Scale = 1 : 3000
1 inch = 250 feet

125 0 250ft

State Plane Coordinate System
Colorado Central Zone
Datum: NAD27

EG&G ROCKY FLATS

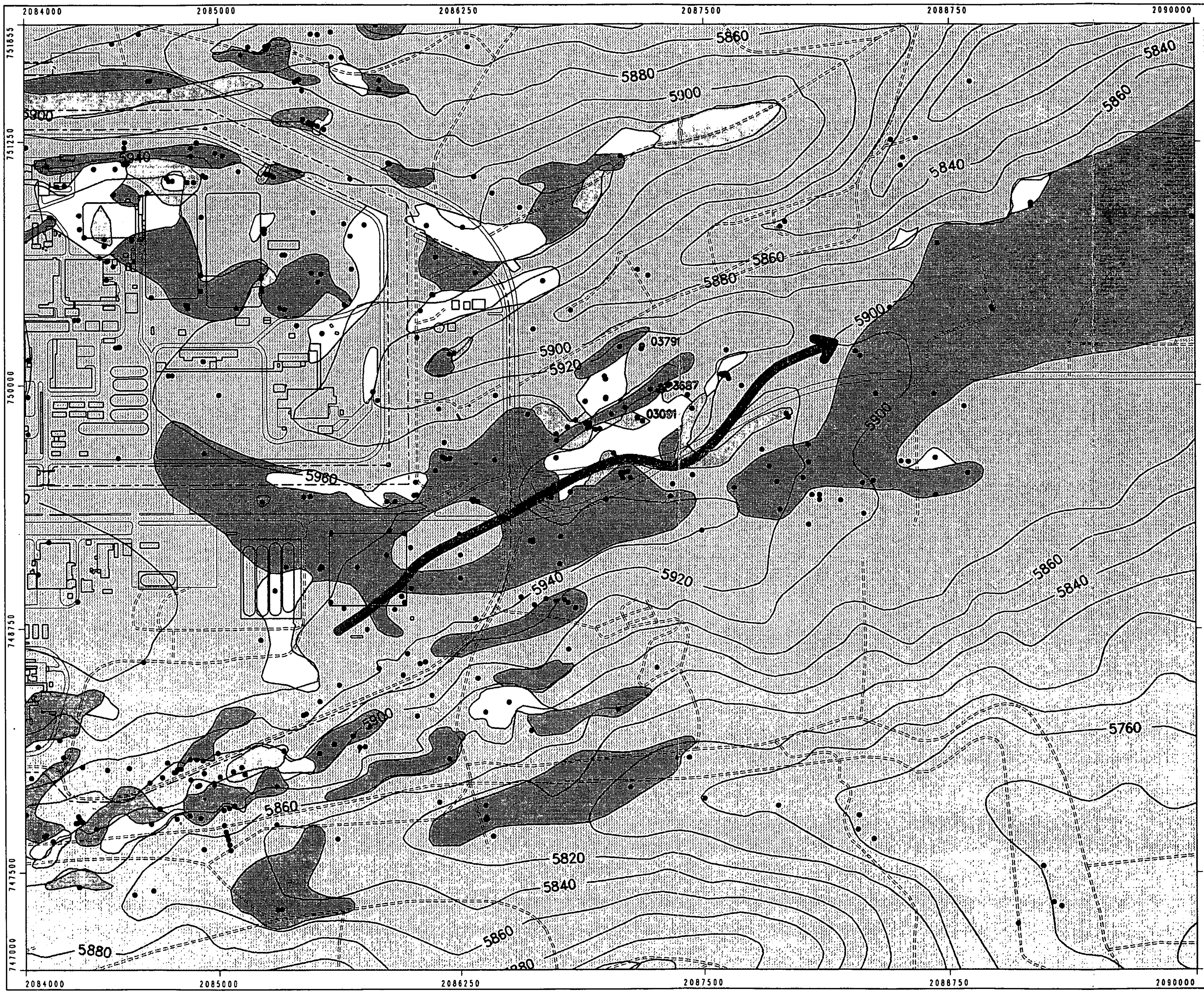
Rocky Flats Site, Golden, Colorado

Potentiometric Surface Map
of Weathered Bedrock
at Present Landfill Area
March 1993
(from: DOE, 1994a)

Hydrogeologic Characterization Report

April 1995	Figure 6-7

192



EXPLANATION

- Monitoring Well
- No. 1 Sandstone Well
- Top of Bedrock Contours
- Paved Roads
- Dirt Roads
- Rocky Flats Plant Site and Security Zone Boundaries
- Buildings
- Claystone
- Silty Claystone, Sandy Claystone
- Sandstone, Clayey Sandstone, and Silty Sandstone
- Siltstone, Clayey Siltstone, and Sandy Siltstone
- Approximate Extent and Trend of Medial Paleoscour

N

Scale = 1 : 6000
1 inch = 500 feet

250 0 500ft

State Plane Coordinate System
Colorado Central Zone
Datum: NAD27

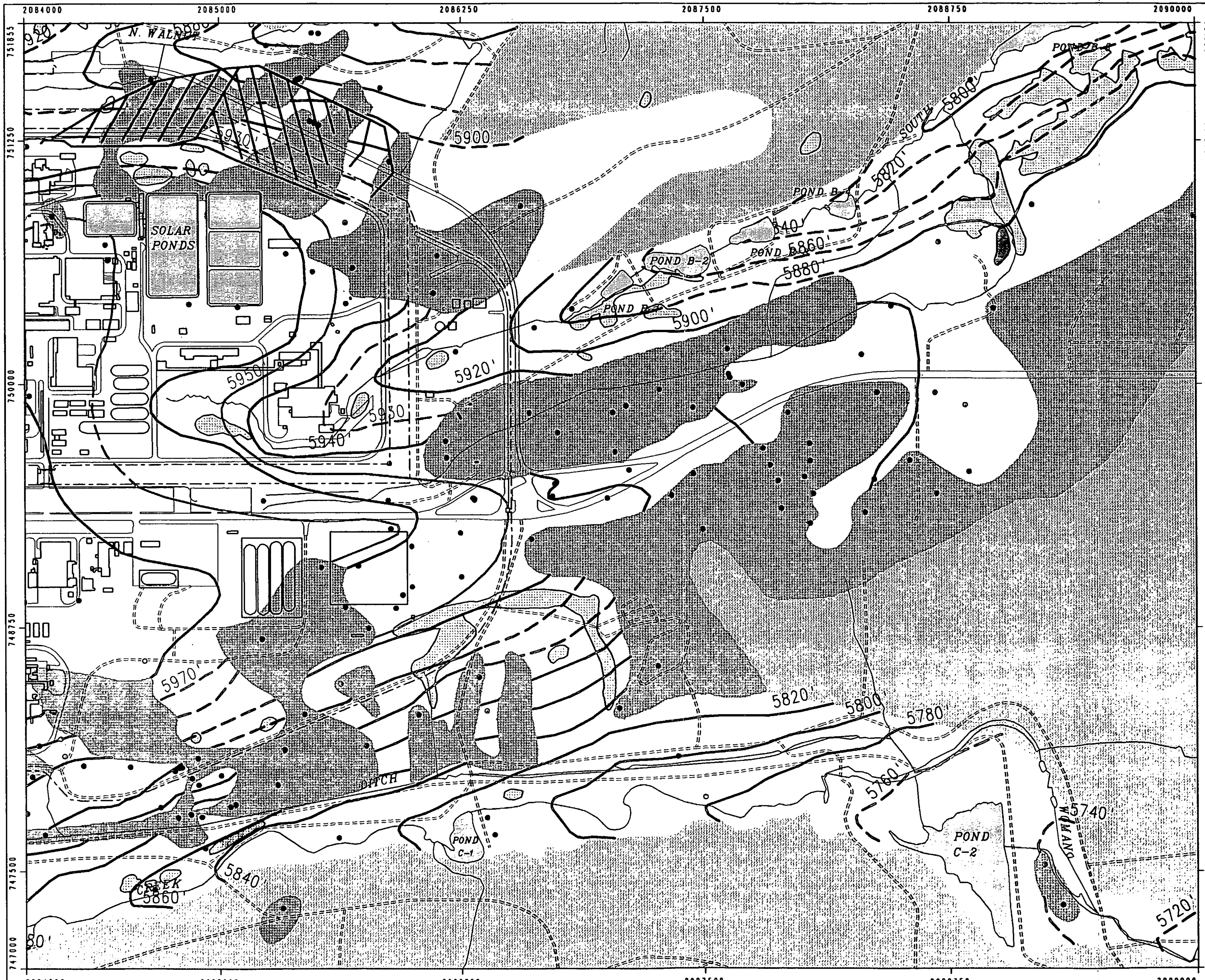
EG&G ROCKY FLATS

Rocky Flats Site, Golden, Colorado

Eastern Industrial Area Subcropping Lithology and Bedrock Elevation Map Showing Medial Paleoscour

Hydrogeologic Characterization Report

April 1995 | Figure 6-10



EXPLANATION

- Wells with 2nd Quarter Potentiometric Data
- Water Level Contour
- Intermediate Water Level Contour
- Paved Roads
- Dirt Roads
- Rocky Flats Plant Site and Security Zone Boundaries
- French Drain
- Approximate Extent of Unsaturated Areas
- Perennial Seep
- Ephemeral Seep
- Areas Without Groundwater Elevation Data
- Surface Water Impoundments
- Buildings

N

Scale = 1 : 6000
1 inch = 500 feet

250 0 500ft

State Plane Coordinate System
Colorado Central Zone
Datum: NAD27

EG&G ROCKY FLATS

Rocky Flats Site, Golden, Colorado

Potentiometric Surface in Unconsolidated Surficial Deposits of the Eastern Industrial Area Second Quarter 1993

Hydrogeologic Characterization Report

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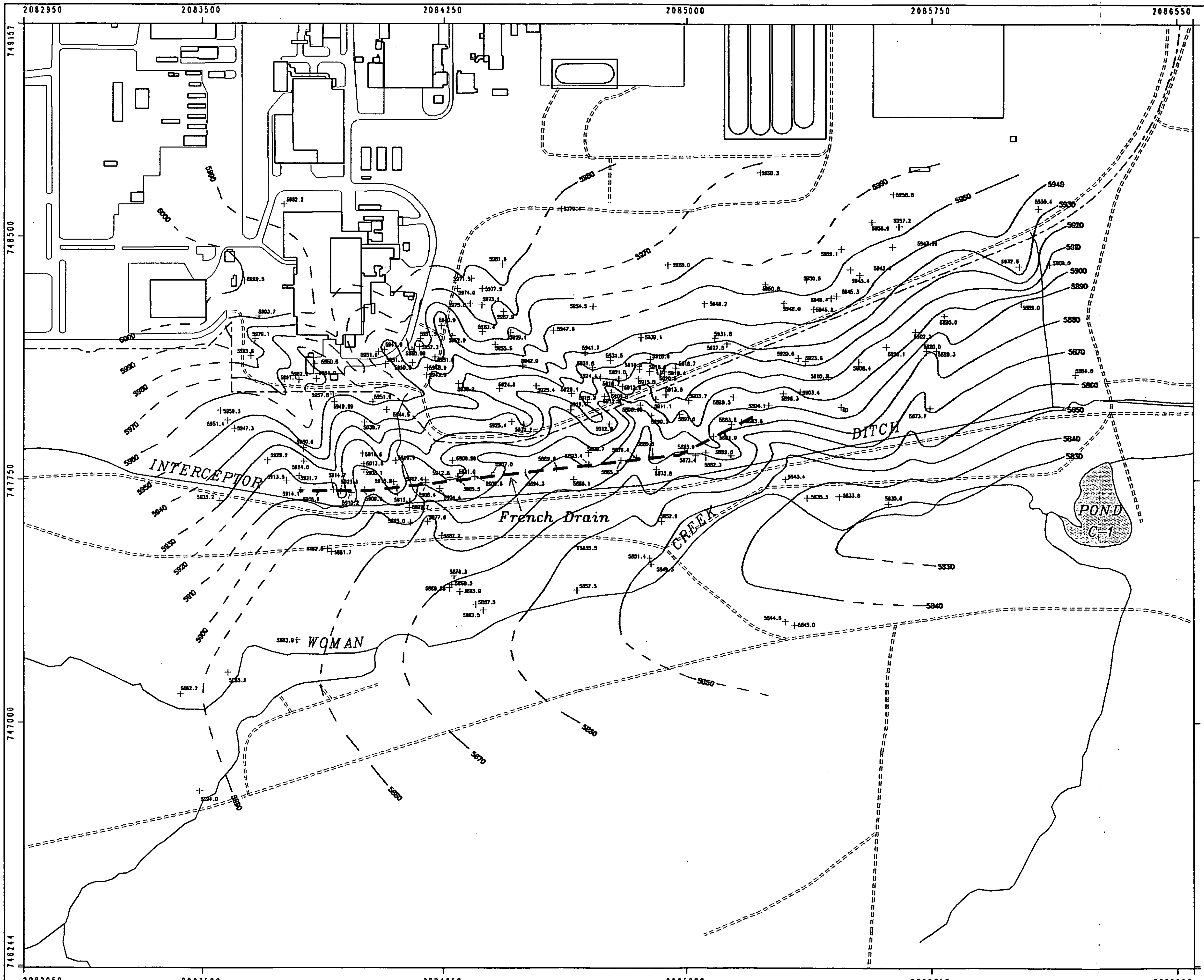
195



EXPLANATION

- + Control Point Showing Bedrock Elevation in Feet
- Bedrock Topography (dashed where inferred)
- French Drain
- Streams and Drainages
- Paved Roads
- Dirt Roads
- Rocky Flats Plant Site and Security Zone Boundaries
- Surface Water Impoundments
- Buildings

Scale = 1 : 3600
1 inch = 300 feet

150 0 300ft

State Plane Coordinate System
Colorado Central Zone
Datum: NAD27

EG&G ROCKY FLATS

Rocky Flats Site, Golden, Colorado

Bedrock Topography
of
881 Hillside Area
Operable Unit No. 1
(from: EG&G, 1994c)

Hydrogeologic Characterization Report

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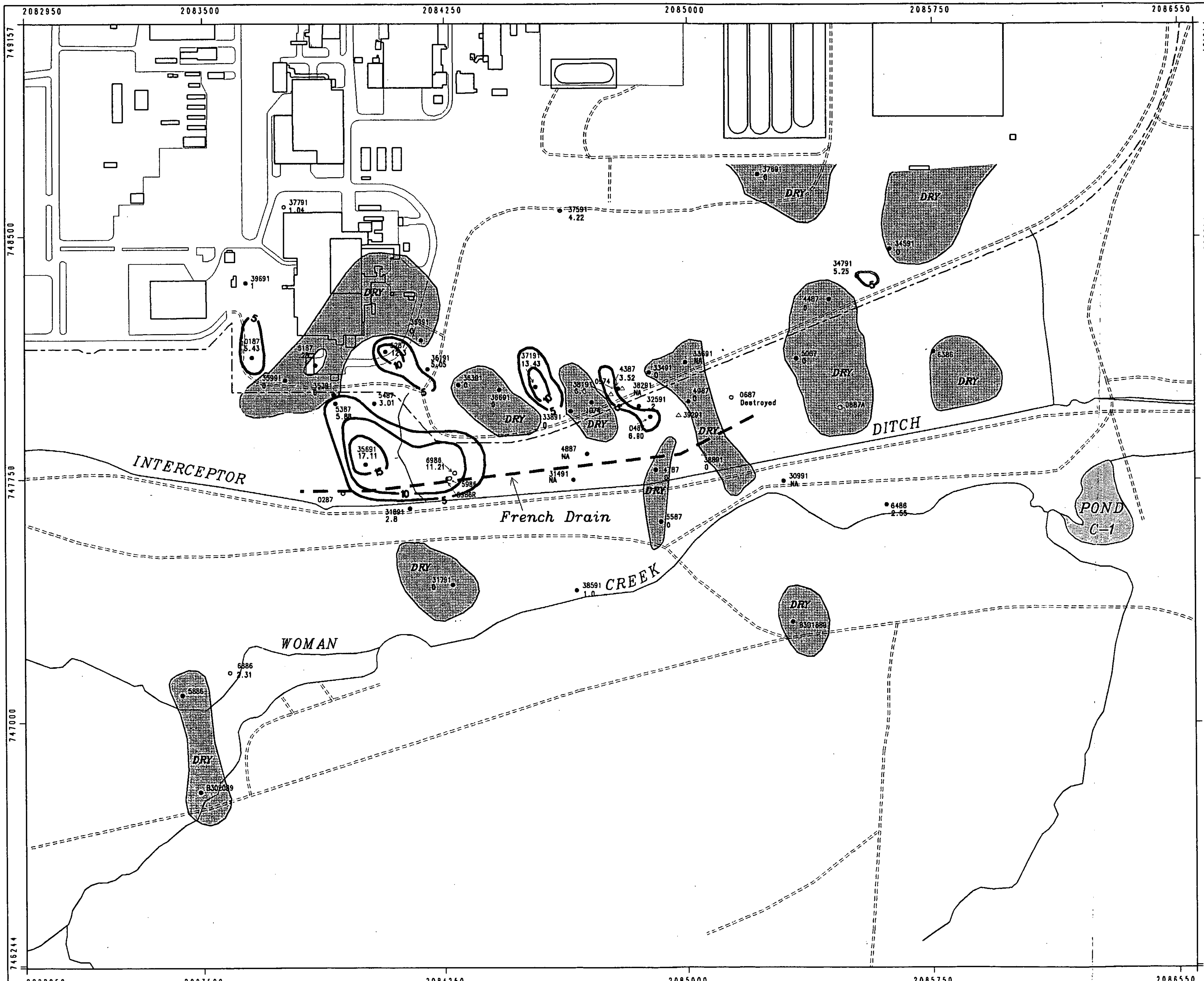


EXPLANATION

- Wells
- Abandoned Wells
- Piezometer
- Line of Equal Saturated Thickness
- French Drain
- Streams and Drainages
- Paved Roads
- Dirt Roads
- Rocky Flats Plant Site and Security Zone Boundaries
- Approximate Extent of Unsaturated Areas
- Surface Water Impoundments
- Buildings

N

Scale = 1 : 3600
1 inch = 300 feet

150 0 300ft

State Plane Coordinate System
Colorado Central Zone
Datum: NAD27

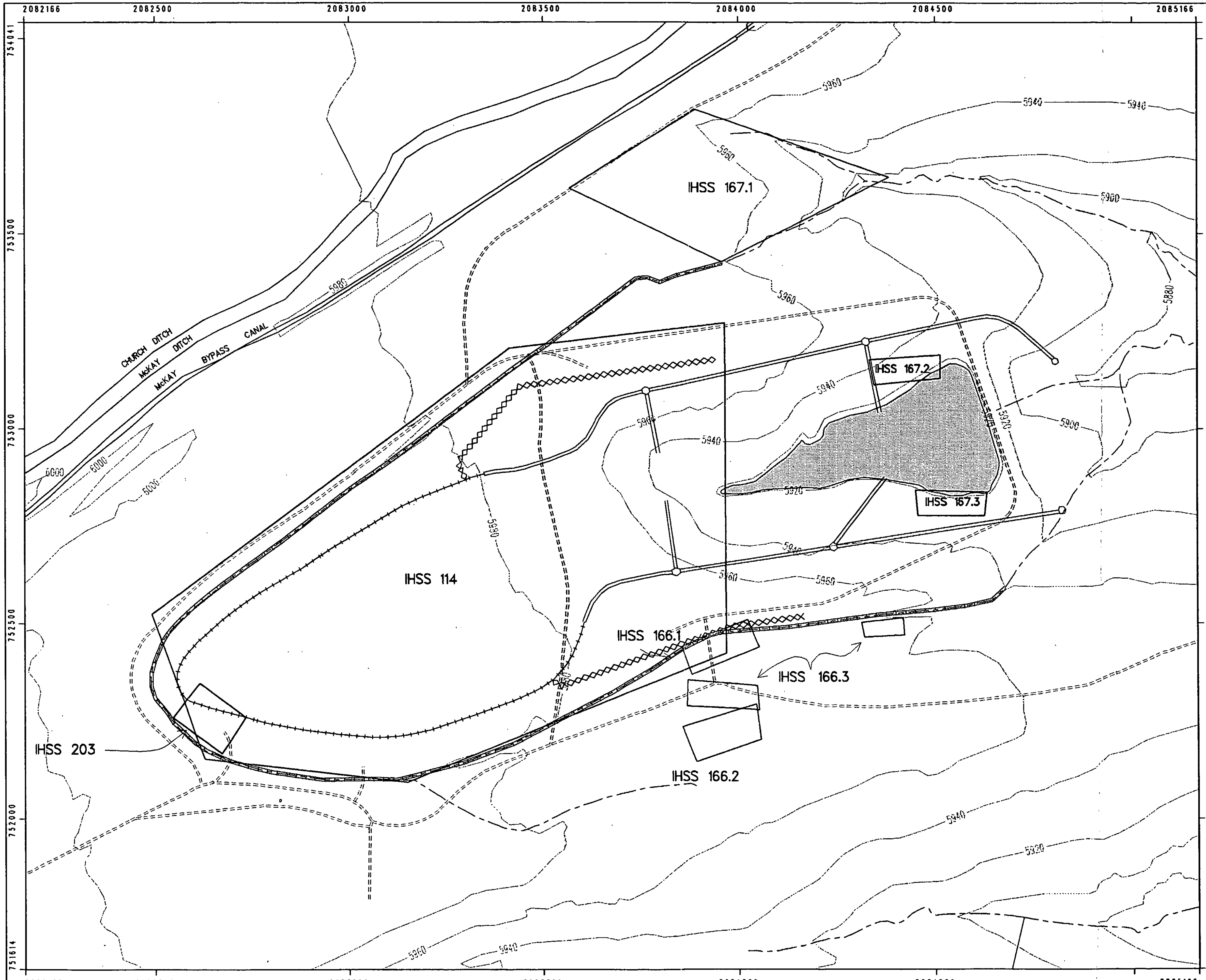
EG&G ROCKY FLATS

Rocky Flats Site, Golden, Colorado

Saturated Thickness of Surficial Deposits in the 881 Hillside Area Operable Unit No. 1 (from: DOE, 1994g)

Hydrogeologic Characterization Report

April 1995	Figure 6-15



EXPLANATION

- Dirt Roads
- Topographic Contours
- Streams and Ditches
- Intermittent Streams
- OU 7 IHSS Boundary
- OU 6 IHSS Boundary
- Surface-Water Diversion Ditch
- Slurry Wall
- Groundwater Intercept System
  - (perforated)
  - (non-perforated)

Scale = 1 : 3000
1 inch = 250 feet

125 0 250ft

State Plane Coordinate System
Colorado Central Zone
Datum: NAD27

EG&G ROCKY FLATS

Rocky Flats Site, Golden, Colorado

Locations of Landfill Structures, Operable Unit No. 7 (from: DOE, 1994a)

Hydrogeologic Characterization Report

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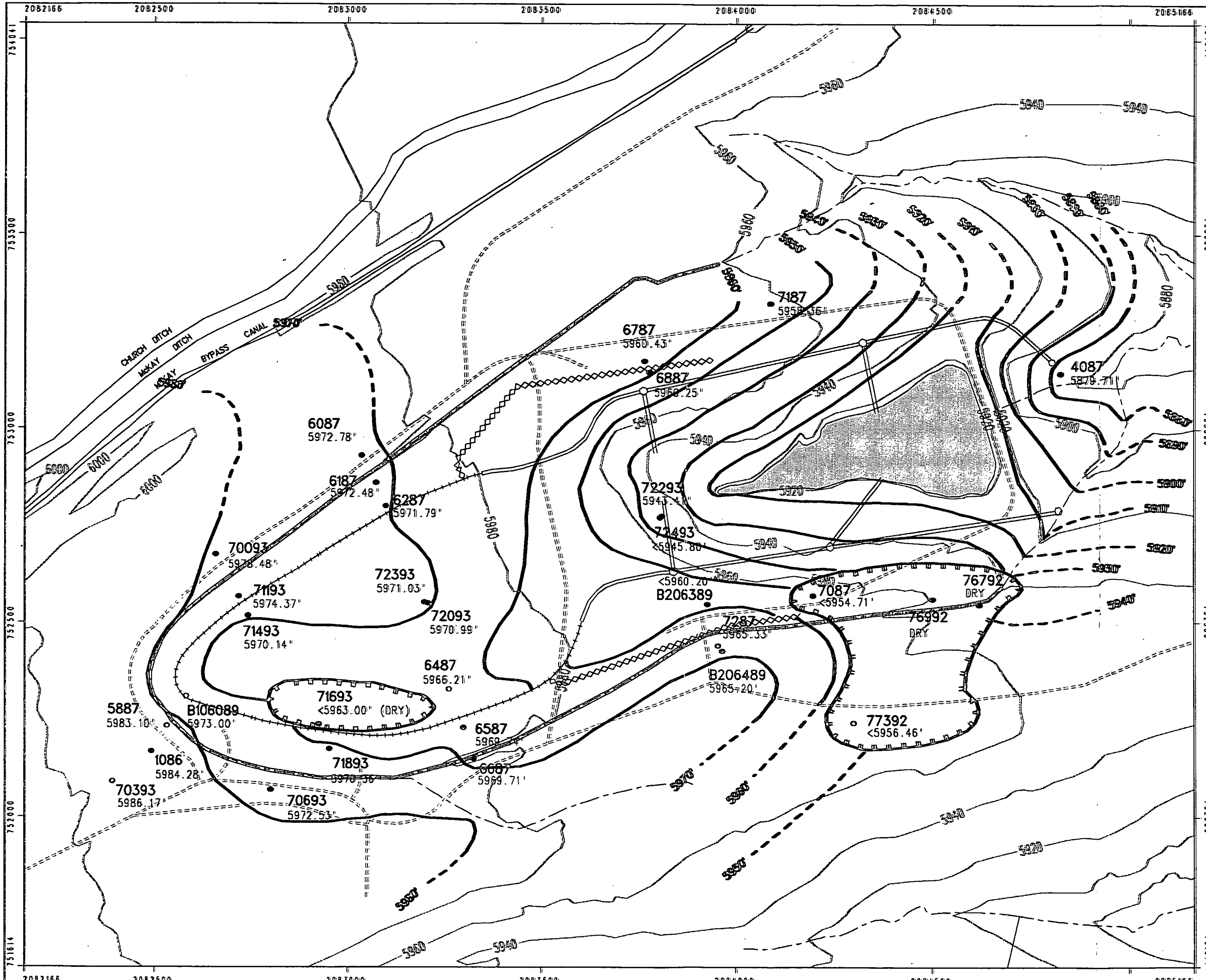


EXPLANATION

- Alluvial Well
- Line of Equal Potentiometric Surface
- (dashed where inferred)
- Areas of Unsaturated Surficial Material
- (dashed where inferred)
- Dirt Roads
- Topographic Contours
- Streams and Ditches
- Intermittent Streams
- Surface-Water Diversion Ditch
- Slurry Wall
- Groundwater Intercept System
- (perforated)
- (non-perforated)
- Water Level Measured Below Screened Interval
- Screened in Surficial Materials and Weathered Bedrock

Scale = 1 : 3000
1 inch = 250 feet

State Plane Coordinate System
Colorado Central Zone
Datum: NAD27

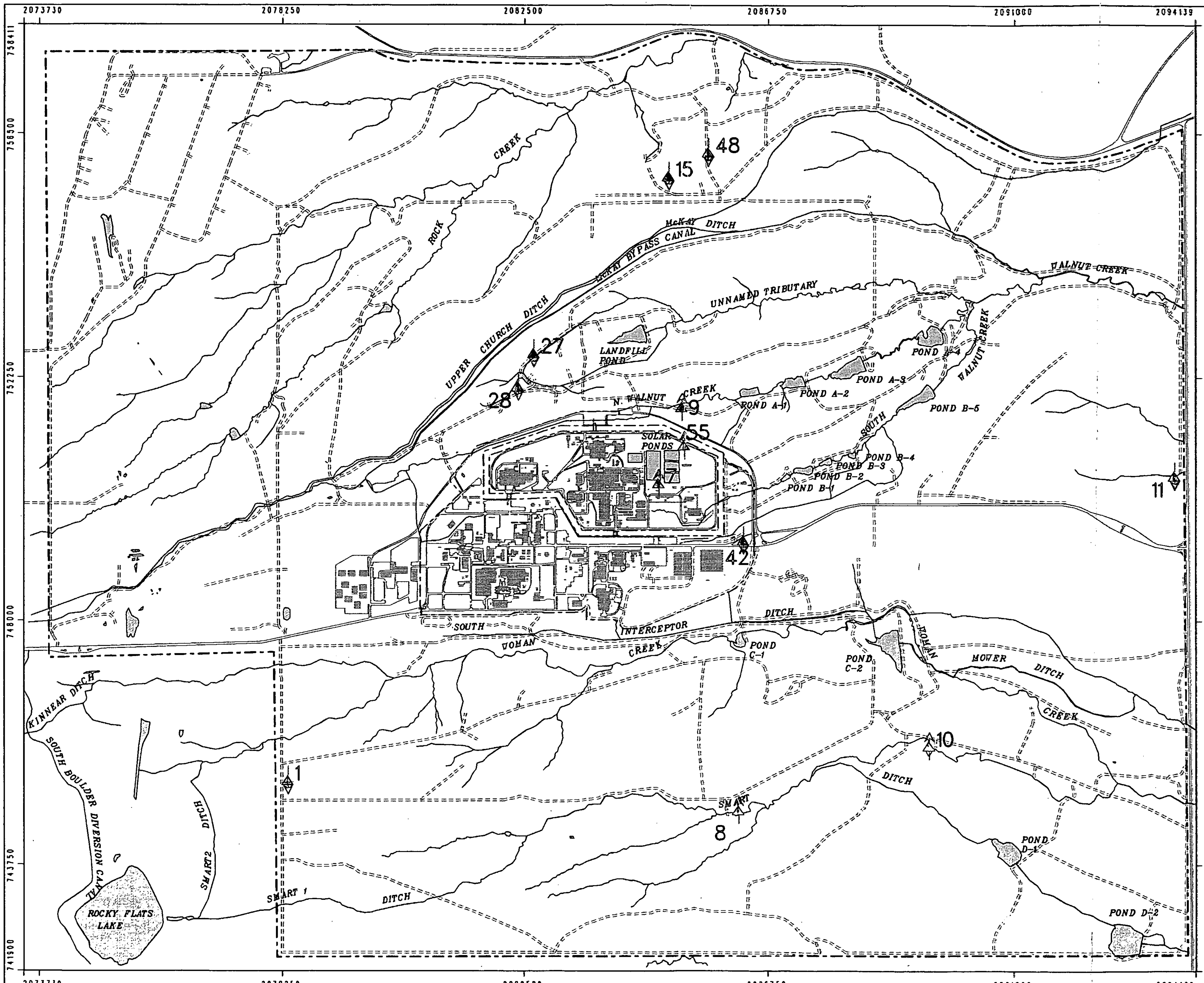
EG&G ROCKY FLATS

Rocky Flats Site, Golden, Colorado

Potentiometric Surface Map of Surficial Material at Present Landfill Area March 1993 (from: DOE, 1994a)

Hydrogeologic Characterization Report

April 1995 | Figure 6-17



EXPLANATION

Completion Zone

Weathered Bedrock
Unweathered Bedrock

Upward Vertical Hydraulic Gradient

Downward Vertical Hydraulic Gradient

Streams and Drainages

Paved Roads

Dirt Roads

Rocky Flats Plant Site and Security Zone Boundaries

Rocky Flats Site Boundary

Surface Water Impoundments

Buildings

Scale = 1 : 20400
1 inch = 1700 feet

850 0 1700ft

State Plane Coordinate System
Colorado Central Zone
Datum: NAD27

EG&G ROCKY FLATS

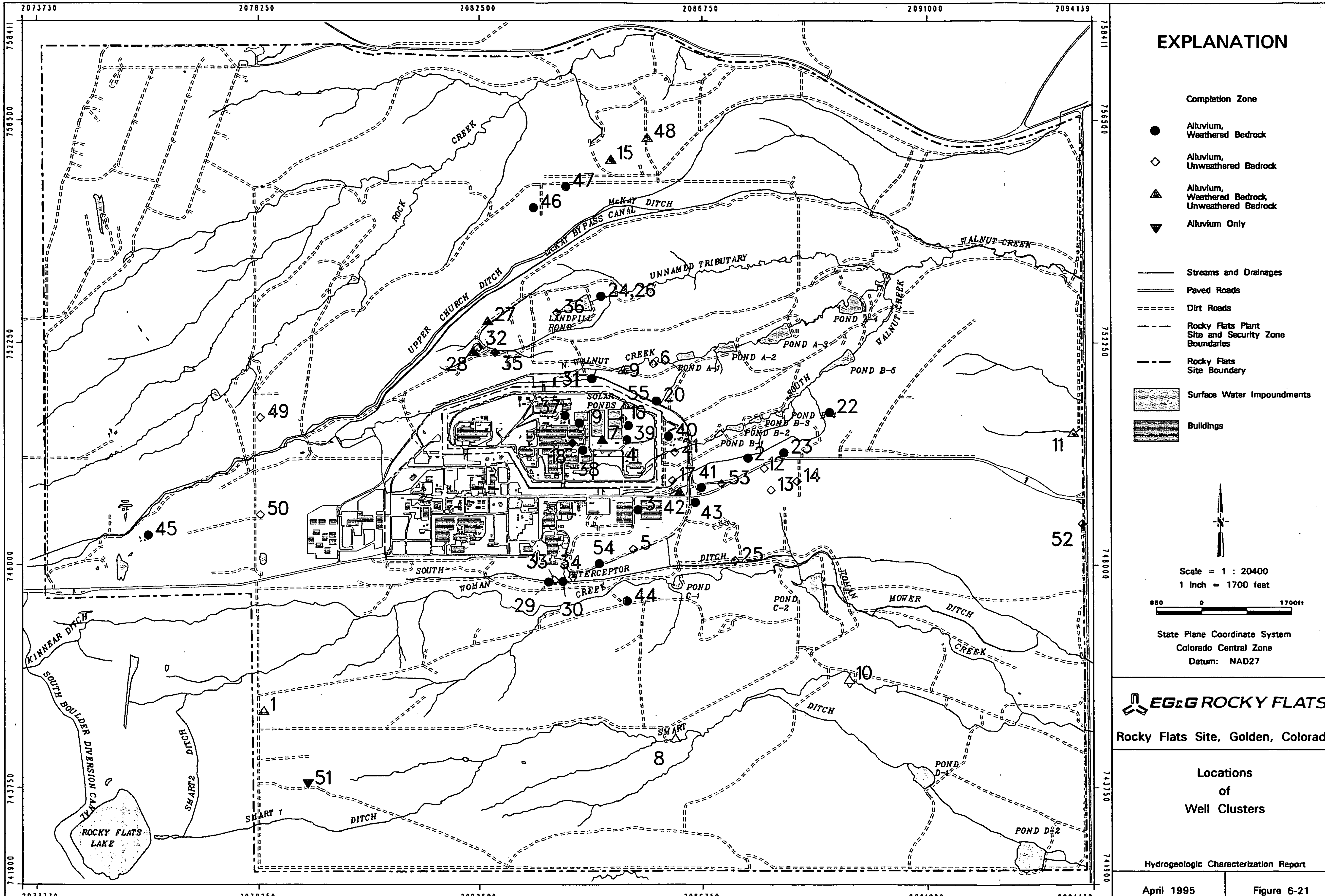
Rocky Flats Site, Golden, Colorado

Vertical Hydraulic Gradients Between Weathered and Unweathered Bedrock

Hydrogeologic Characterization Report

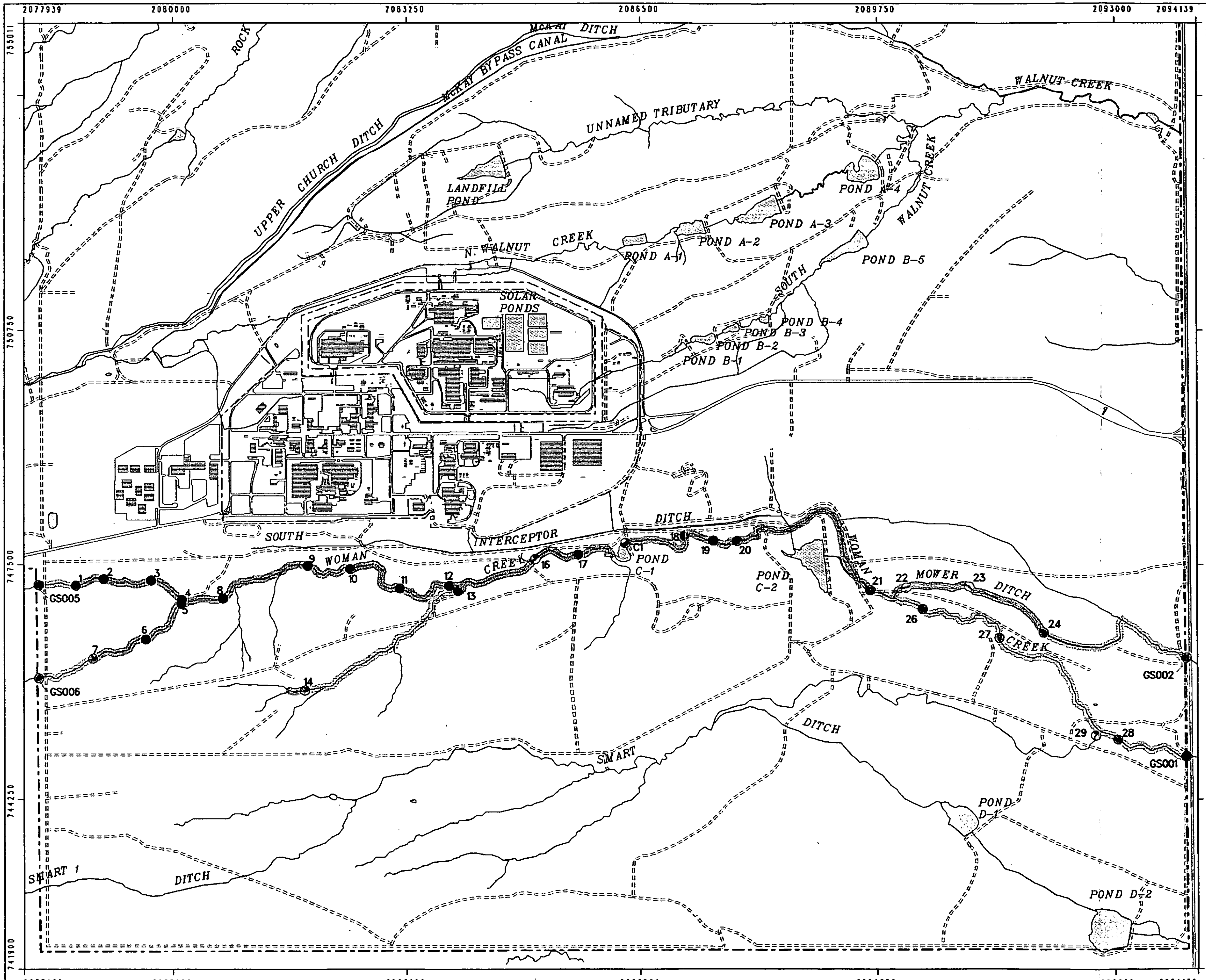
April 1995

Figure 6-19



EXPLANATION
Completion Zone
Alluvium, Weathered Bedrock
Alluvium, Unweathered Bedrock
Alluvium, Weathered Bedrock, Unweathered Bedrock
Alluvium Only
Streams and Drainages
Paved Roads
Dirt Roads
Rocky Flats Plant Site and Security Zone Boundaries
Rocky Flats Site Boundary
Surface Water Impoundments
Buildings
Scale = 1 : 20400
1 inch = 1700 feet
State Plane Coordinate System
Colorado Central Zone
Datum: NAD27
EG&G ROCKY FLATS
Rocky Flats Site, Golden, Colorado
Locations of Well Clusters
Hydrogeologic Characterization Report
April 1995
Figure 6-21
2073730
2078250
2082500
2086750
2091000
2094139
758411
756500
752250
748000
743750
741900
ROCK CREEK
McKAY DITCH
McKAY BYPASS CANAL
UPPER CHURCH DITCH
WALNUT CREEK
UNNAMED TRIBUTARY
LANDFILL POND
N. WALNUT CREEK
POND A-1
POND A-2
POND A-3
POND A-4
POND B-1
POND B-2
POND B-3
POND B-4
POND B-5
SOUTH WALNUT CREEK
SOLAR PONDS
SOUTH INTERCEPTOR DITCH
WOMAN CREEK
POND C-1
POND C-2
MOWER DITCH
KINNEAR DITCH
SOUTH BOULDER DIVERSION CANAL
SMART 2 DITCH
SMART 1 DITCH
SMART DITCH
POND D-1
POND D-2
ROCKY FLATS LAKE

205



EXPLANATION

General Segment Classification

- Stream Gains Year-Round
- Stream Gains During Spring (December - March or April) Loses Rest of Year
- Stream Loses Year-Round
- Stream Experiences a Gain For 2 Months or Less During Year, Loses Rest of Year
- Creek Not Classified Due to Inadequate or Uncalibrated Data
- Measurement Location
- Surface Water Impoundments
- Buildings
- Streams and Drainages
- Paved Roads
- Dirt Roads
- Rocky Flats Plant Site and Security Zone Boundaries
- Rocky Flats Site Boundary

Scale = 1 : 16200
1 inch = 1350 feet

675 0 1350ft

State Plane Coordinate System
Colorado Central Zone
Datum: NAD27

EG&G ROCKY FLATS

Rocky Flats Site, Golden, Colorado

Woman Creek
Infiltration/Exfiltration
Stream Segment Classification

Hydrogeologic Characterization Report

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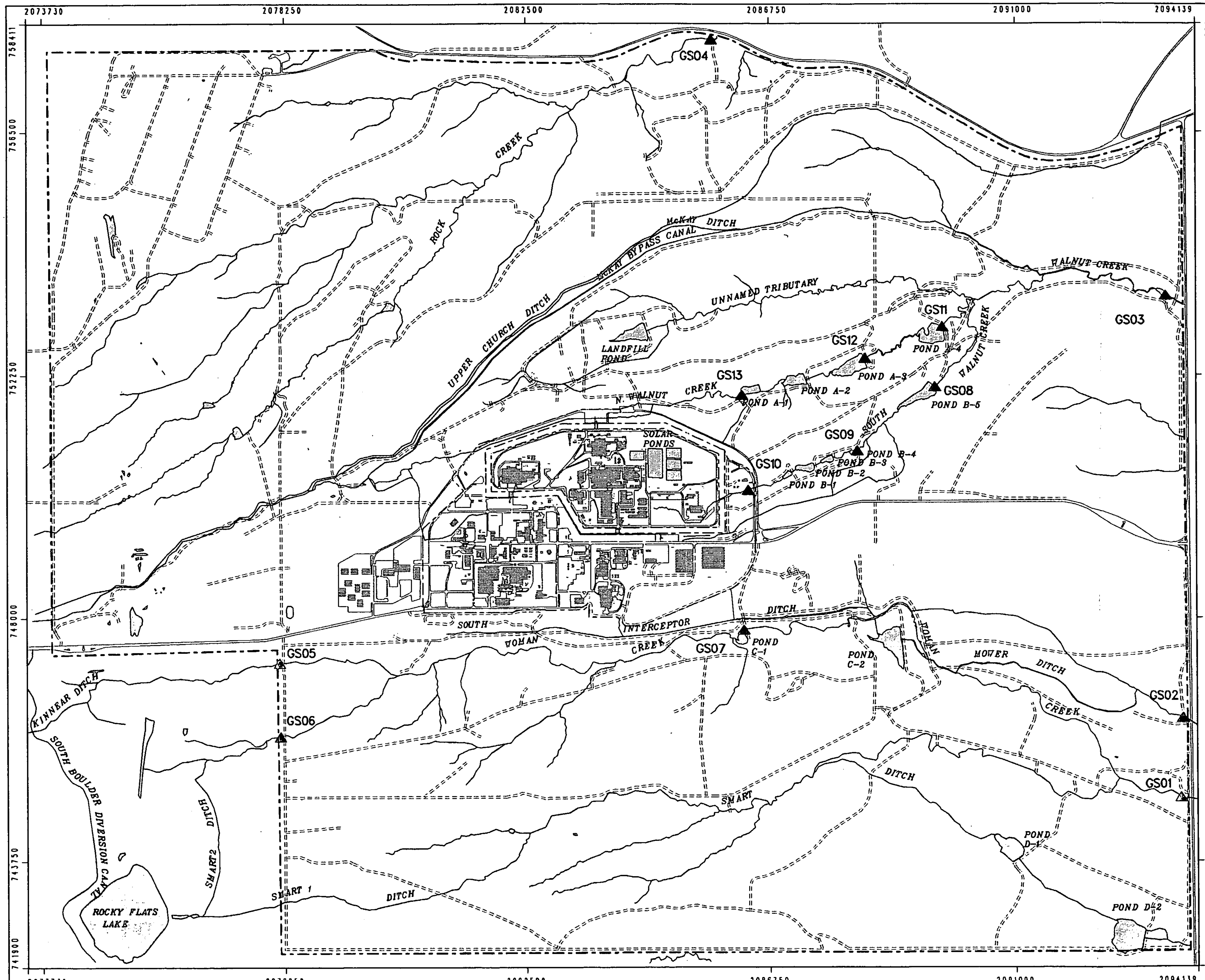

EXPLANATION

- Stream Gaging and Sampling Stations
- Streams and Drainages
- Paved Roads
- Dirt Roads
- Rocky Flats Plant Site and Security Zone Boundaries
- Rocky Flats Site Boundary
- Surface Water Impoundments
- Buildings

N

Scale = 1 : 20400
1 inch = 1700 feet

850 0 1700ft

State Plane Coordinate System
Colorado Central Zone
Datum: NAD27

EG&G ROCKY FLATS

Rocky Flats Site, Golden, Colorado

Sitewide
Gaging Station
Network

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